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30 kWe Class High Efficiency Arcjet Power Conditioner
Volume I

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NOTICE

FOREWORD

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This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

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A 30 kWe arcjet PCU has been designed, built and tested, both with a solid state load and with a 30 kWe arcjet thruster. The arcjet PCU has accumulated over 40 hours full power or nearly full power operating time, and showed no sign of degradation. The measured efficiency was 94%, which can easily be increased to 95% by substitution of some recently available semiconductors. The stability of output current has been demonstrated while using current-mode, pulse-width modulation control.

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OBJECTIVES

The objective of this project is to design, construct and proof-test an arcjet power conditioning unit (PCU) for supplying and controlling the electric power delivered to a 30 kWe arcjet engine. The PCU must also be capable of generating a high voltage spike to initiate the arc. The arcjet PCU is to have a high degree of current stability and an efficiency of about 95%. Proof-testing is to be conducted on an actual 30 kWe arcjet.

PROGRESS HISTORY

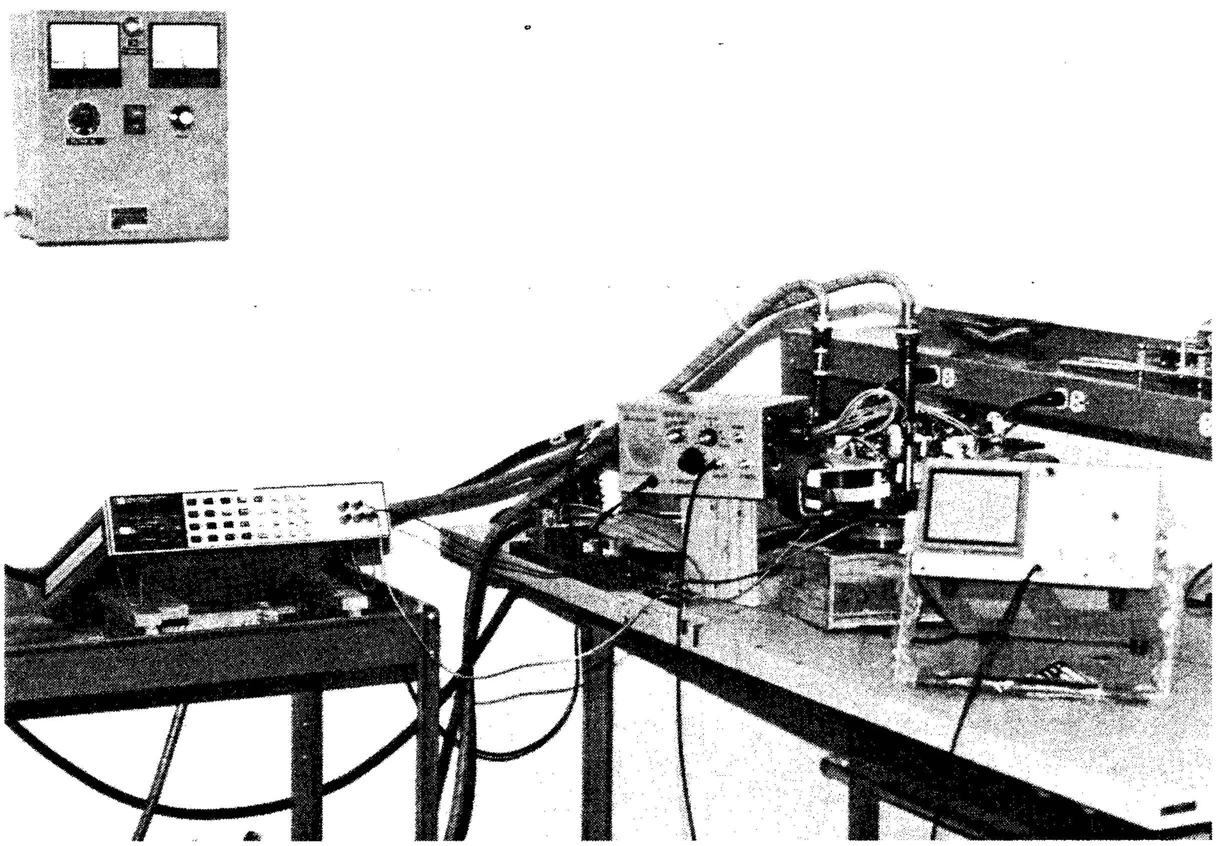
BASIC DESIGN PHILOSOPHY

The design approach of an arcjet power conditioning unit (PCU) depends on whether the power source voltage is higher or lower than the arcjet operating voltage. If the supply voltage of the main bus is less than that required by the arcjet, a power conditioning concept which produces voltage step-up must be used. On the other hand, if the main bus voltage is greater than the arcjet operating voltage, a controlling type of buck regulator will be appropriate.

The voltage issue has been carefully considered by SPI, RRC and AFAL with the following conclusion: Any spacecraft application capable of producing the required power for 30 kWe arcjet operation must have a main bus voltage of approximately 150 volts DC or higher. For example, a nuclear reactor system must have voltage in this range to transmit power down the 25-meter separation boom. If solar panels are the spacecraft power source, the long dimensions of a high power solar array will also require a high voltage bus. If the power source does not generate a voltage greater than 100 volts DC, a separate power conditioner to provide voltage boost can be included in the system. As a consequence, the selected approach is to design the arcjet electronics for an input voltage of 150 volts from the power source.

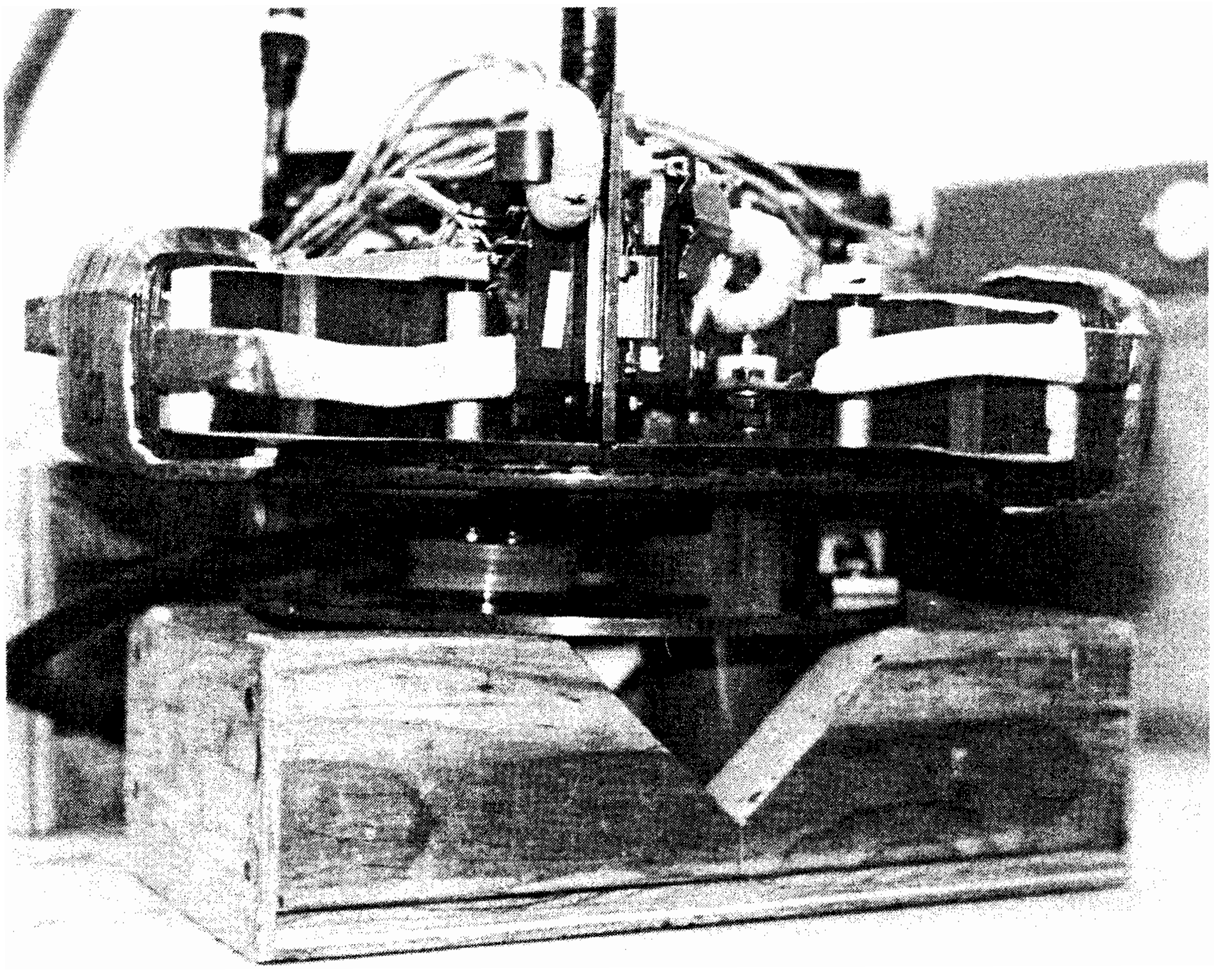
A buck regulator design, Figure 1, has been selected as the most appropriate circuit for the baseline arcjet. This approach was chosen because of superior efficiency, reliability and compactness. The circuit has advantages of simplicity, small size, and low weight. Because of the reduced number of parts, the reliability will be high.

To reduce current ripple and further increase reliability, three buck regulators will be operated in parallel, (i.e., three-phase operation). The corresponding circuit is shown in Figure 2. In this figure, each of the switch symbols represents a



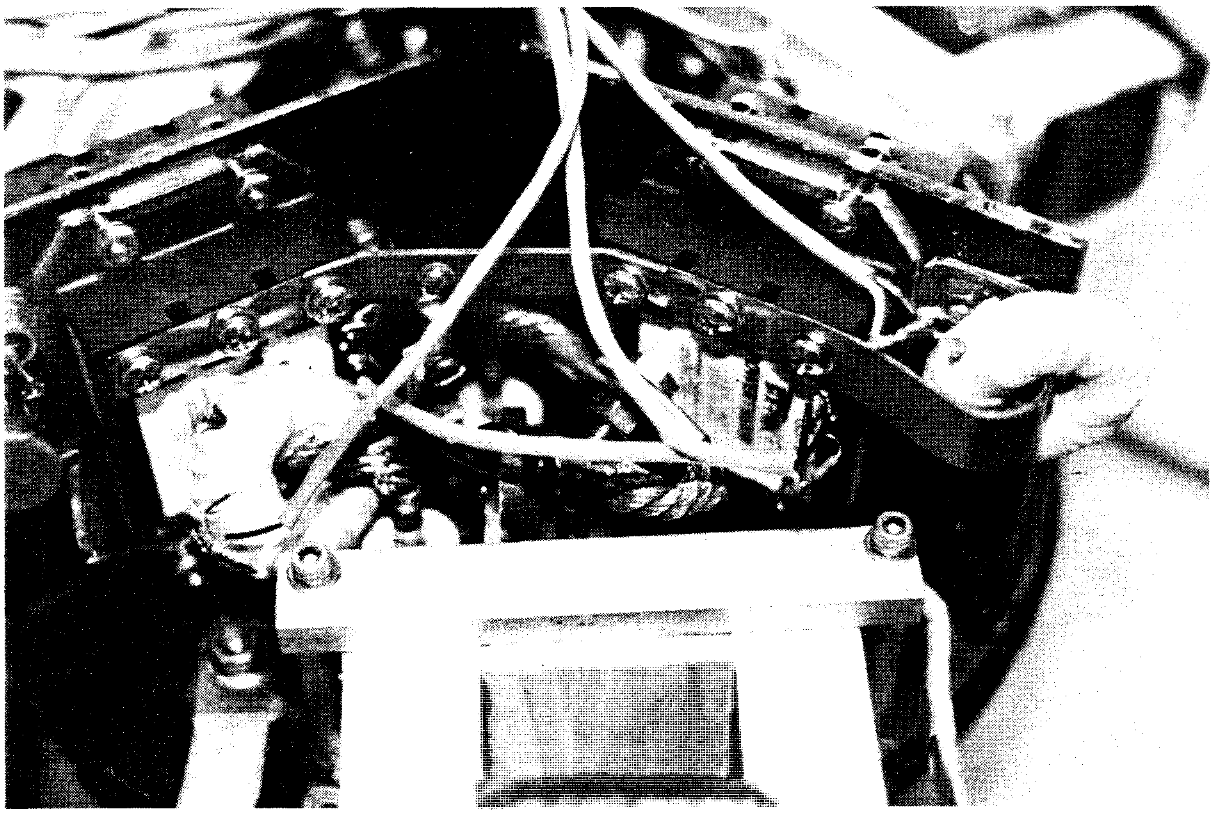
30 kWe Solid State Load

Figure 1a. **<u>Buck Regulator Design</u>**



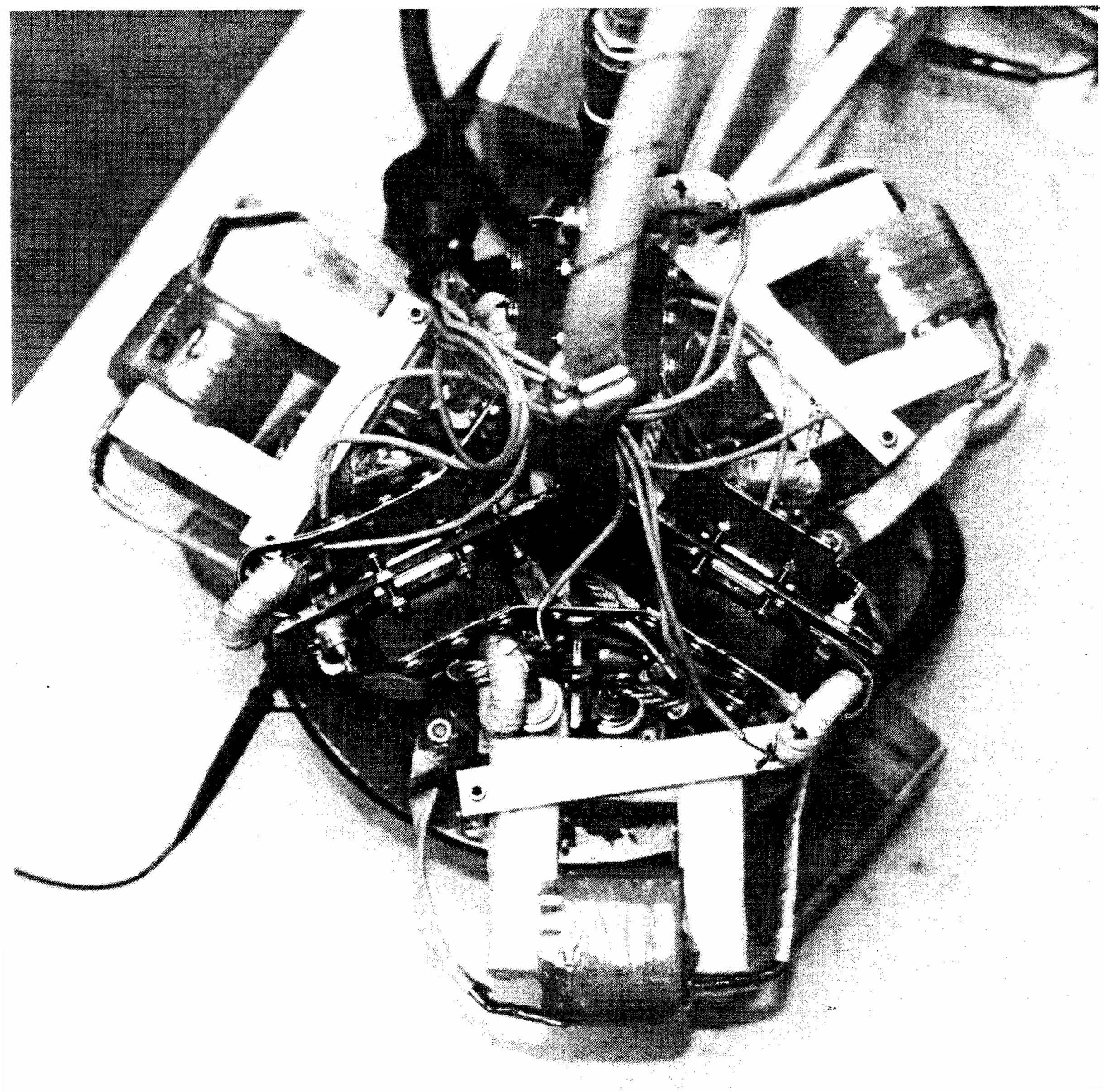
Side View of 30 kWe PCU

Figure 1b. Buck Regulator Design



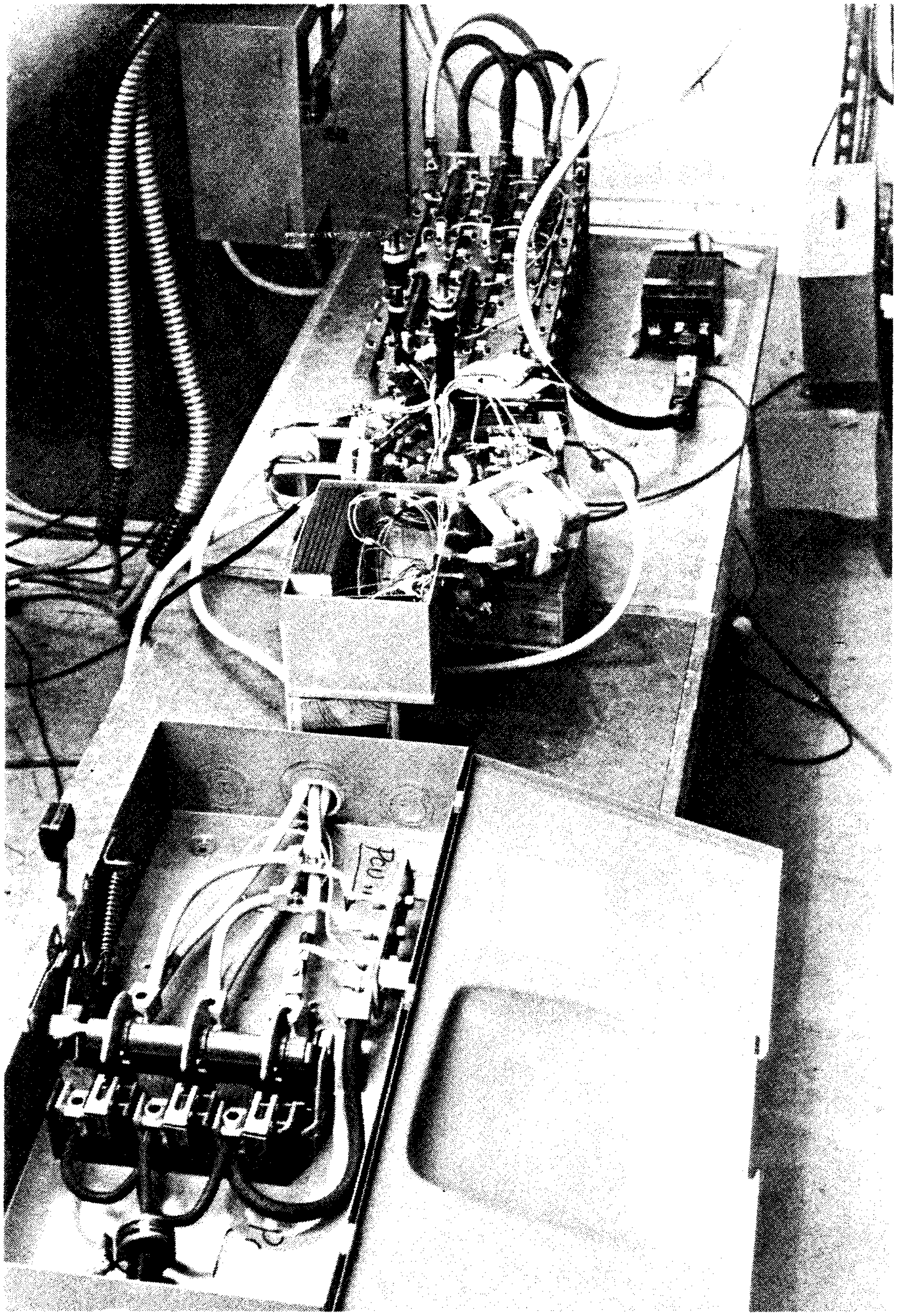
Close-up of A-Phase, 30 kWe PCU

Figure 1c. **<u>Buck Regulator Design</u>**



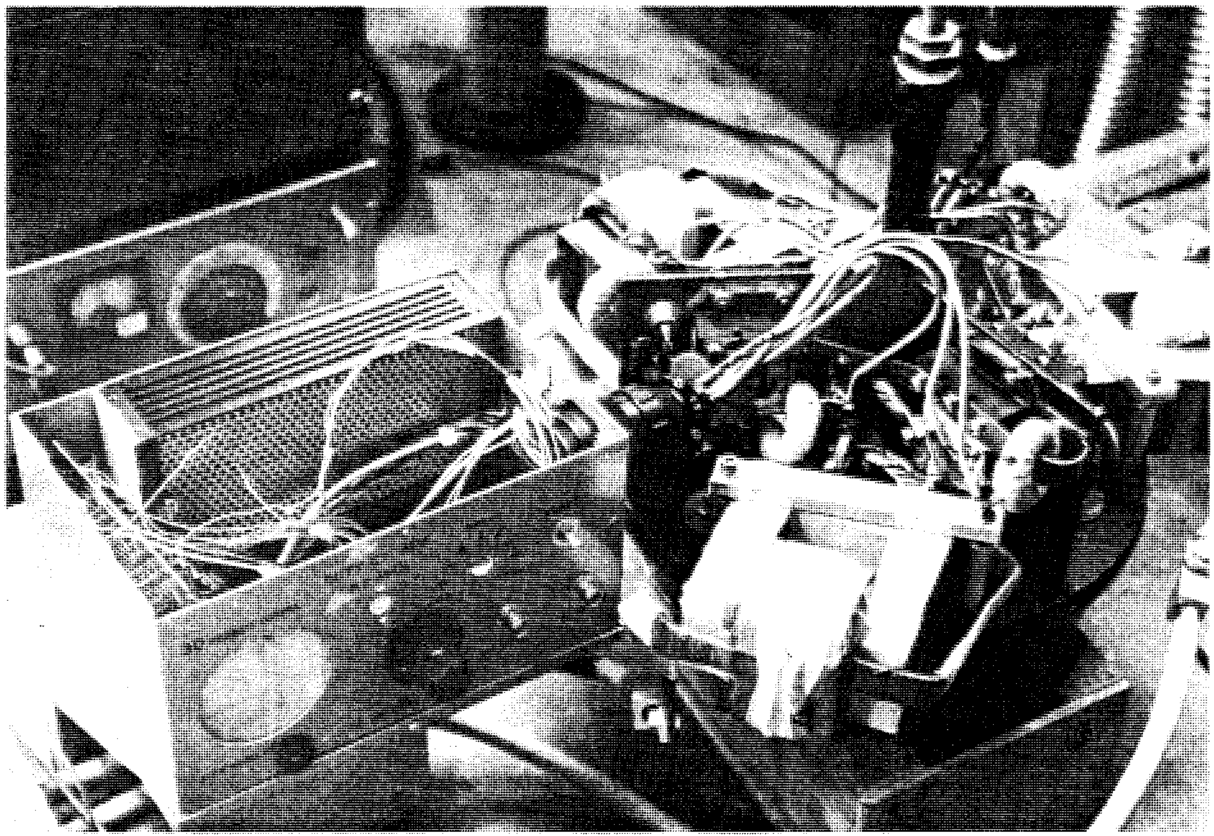
Top View of 30 kWe PCU

Figure 1d. Buck Regulator Design



Test Set-up of 30 kWe Arcjet PCU

Figure 1e. Buck Regulator Design



Test Set-up of Arcjet PCU

Figure 1f. Buck Regulator Design

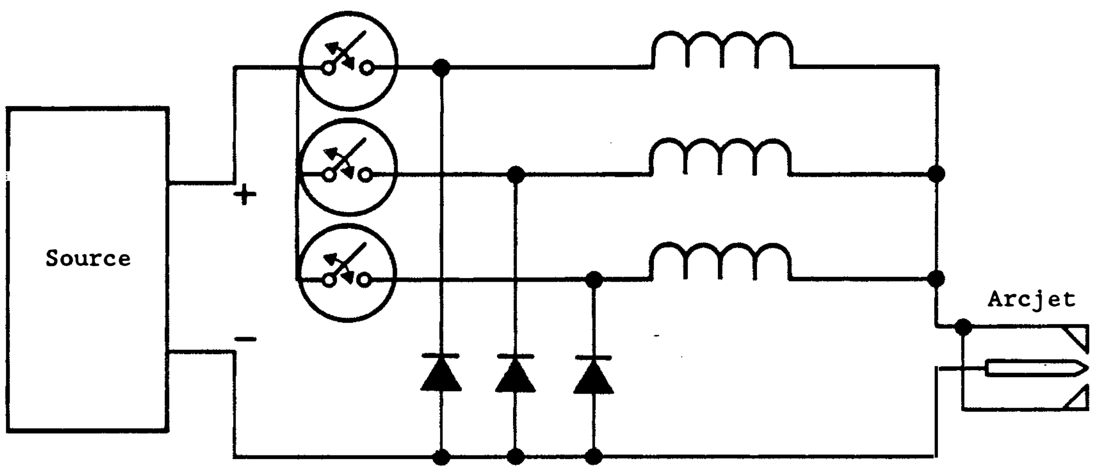


Figure 2. Simplified Conceptual Schematic of a 3 Phase Regulator for Arcjet Current Control

parallel group of high-current hybrid metal oxide semiconductor field effect transistors (MOSFET). With this circuit, redundancy can be built in, so that one phase can fail and the other two will still have sufficient capacity to ensure proper operation.

The switches for the arcjet power conditioner with buck regulator operate at approximately 20 kHz. The switches are fired 120° out of phase to provide smoother regulation, as shown in Figure 3. The current in each of the three phases is interrupted in a staggered sequence to complete one cycle. The current in one phase rises while its switch is closed, and the current in the interrupted phase decreases.

The PCU will operate the arcjet at a continuously adjustable level of constant current. The conditioner must accommodate the arcjet I-V characteristics, which include negative dynamic resistance. The characteristics are complex and vary with time over a broad frequency spectrum. This requires monitoring the arcjet operating current and using feedback to control the drive timing. With this approach, the arcjet current remains constant despite the changing arcjet I-V characteristics an/or varying power source voltage.

A more complete description of the feedback control circuit is shown in Figure 4. A current measuring shunt generates a voltage proportional to the output current. This voltage is compared with the voltage corresponding to a desired current level to produce an error voltage. The time integral of this error voltage is then used to set the peak current of each of the three phases. The desired current may either be selected by the operator or derived from an operator specified current level.

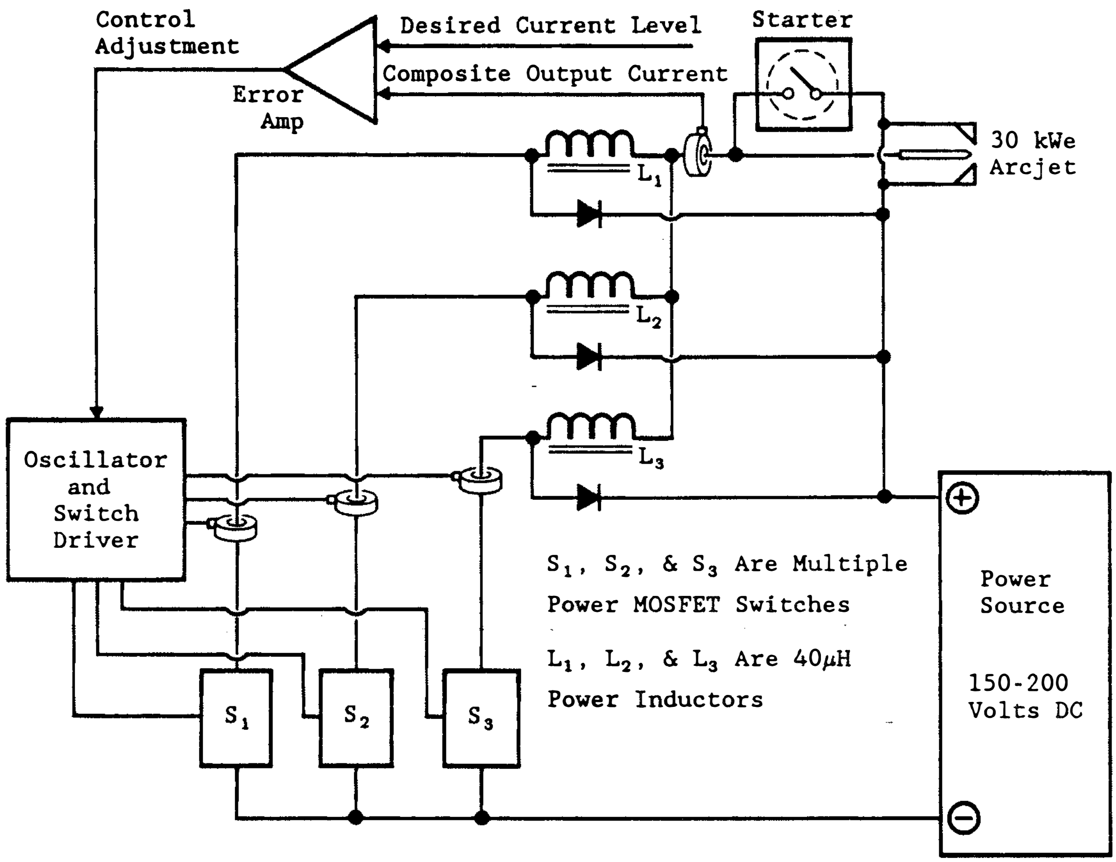


Figure 3. Three Phase Buck Regulator

Another high voltage semiconductor switch is connected across the arcjet, as shown in Figure 4, to shunt current for trigger firing at startup. In the startup sequence, this starter switch is closed, allowing the current to reach a predetermined level in the inductors. The starter switch is then opened, producing a high voltage, which transfers the current into the arcjet, initiating the discharge. The starter switch is normally open and is only used for starting.

COMPUTER SIMULATION

Computer simulation was used to confirm the design before breadboard assembly. Simulation results combined with stability analyses indicated that current mode feedback would be preferred over a simple duty cycle modulator. However, a simple constant limit on the peak current will not guarantee stable operation at duty cycles above 50%. Instead of using a constant peak current limit to control the duty cycle, a sawtooth peak current limit is used. The minimum slope the sawtooth

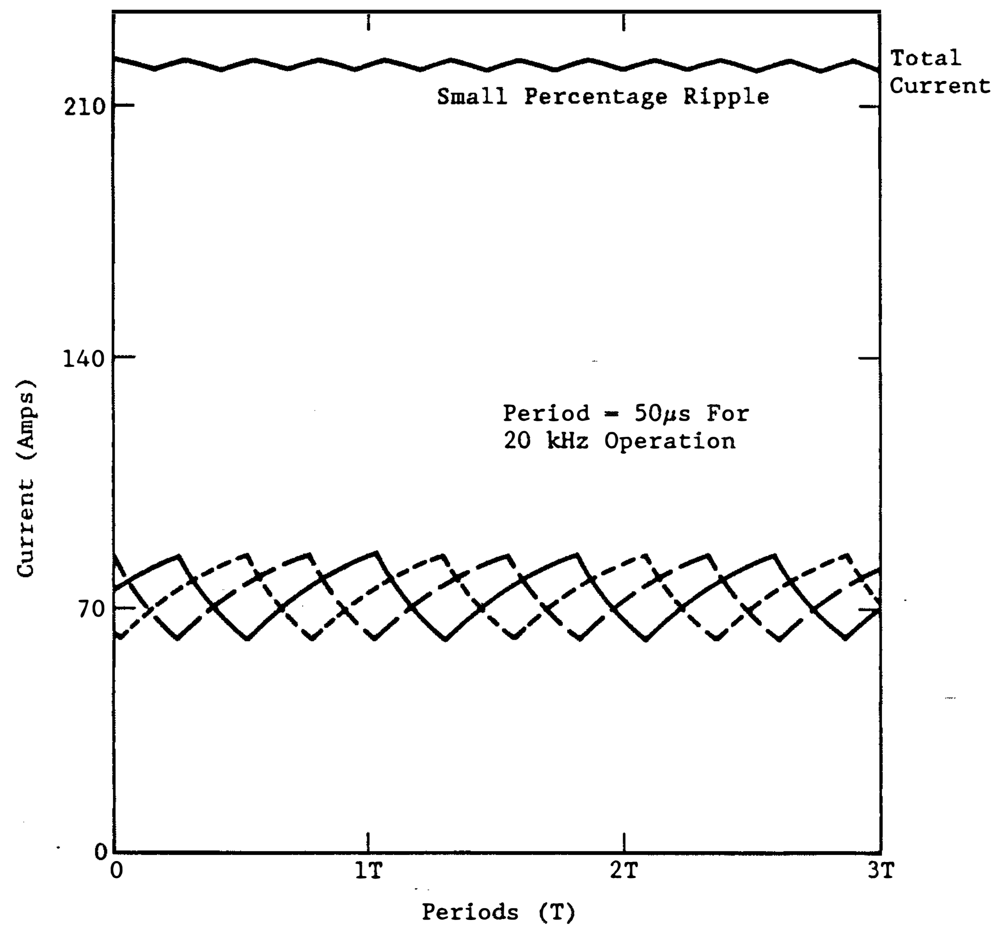


Figure 4. Three Phase Buck Regulator Output

waveform is one half of the slope of the inductor idling current (for details, refer to the Technical Discussion Section). The result was later confirmed in tests with a single phase, reduced power breadboard.

SINGLE PHASE BREADBOARD

A single phase breadboard PCU was developed and used as a forerunner for the full power three phase 30 kWe PCU. The breadboard was designed to handle 10 kWe corresponding to one of the phases in the final three-phase design. Six TO-3 packaged MOSFETs were used in parallel to perform the switching. The Unitrode UC1846 current-mode PWM controller was used as the feedback controller.

Both bipolar transistors and MOSFETs had been previously considered in the single phase breadboard design. But after evaluating the drive complexity, the current density, the system reliability and the switching performance, MOSFETs were selected as the switching components.

Upon completion of the single phase breadboard, it was tested with the arcjet engine at Rocket Research Company (RRC). This test was run without cooling the breadboard. The test was terminated after one and a half minutes because the MOSFETs overheated. Even though the test of the single phase breadboard was very short, it successfully demonstrated the ability of the current-mode buck regulator to control and stabilize the arcjet current without a ballast resistor.

THREE PHASE POWER CONDITIONING UNIT (PCU)

Two possible approaches were evaluated for combining three single-phase buck regulators together to form a three phase interleaved buck regulator. The first approach was to use three independent current servo loops. Each loop would be responsible for keeping a phase current equal to one third of the total arcjet current. This approach has the advantage of uniform sharing of the load current among the three phases. The only matched set of components required to have equal current sharing is the current sensing circuit. The second approach would be to use only a single servo loop to regulate the total output arcjet current instead of individual phases. The advantage of this approach is the simplicity of the control loop. It eliminates the multiloop "cross-talk" oscillation. However, it requires matching and pretesting of the more critical components.

Both approaches were tried. The second approach became the preferred choice after the cross-talk among three phases was identified to be the major hurdle of the three-phase PCU. The cross-talk is introduced by the switching noise of one phase which causes mistriggering of the other two phases. The most switching noise occurs during the "switch on status", due to the reverse recovery of the free wheeling diode. The reverse recovery time of the fastest available diode having a current rating in excess of 100 A, is 200 to 300 nsec. This length of time allows a very high surge current to build up and flow through the free wheeling diode before the diode recovers and blocks current flow. The high surge current thus stops suddenly, when the diode recovers. The high rate of change of the current (di/dt) at recovery generates considerably electromagnetic interference (EMI) which causes the control circuit of the other phases to switch off the MOSFETs prematurely, leading to instability of the PCU. Furthermore, the high surge current also stresses both the MOSFET switches and the free wheeling diodes. An SPI proprietary circuit was used to handle the free wheeling diode, and the surge current due to the finite diode reverse recovery time was thereby reduced to a tolerable level. (See Appendix B).

The noise associated with current measurement also interfered with the current sensing. Shunt resistors were used initially to measure the current. However, in order to minimize the loss in the shunt, the resistance of the shunt, as well as the voltage across it, must be kept to very low values. This made the EMI noise superimposed on the current waveform very significant. Many premature turn offs of the MOSFETs above certain power levels were observed as a result of the noise on the shunt signal. This problem prevented the PCU from full power operation. The problem was resolved by replacing the shunt resistor with a magnetic current sensor (MCS). The MCS technique required more circuits and components, but allowed the voltage level of the current measurement to be raised to a more comfortable level. (See the Technical Discussion section). With this modification, the signal to noise ratio improved enough that interphase cross-talk was confined to right around 33.3% duty cycle and 66.7% duty cycle at which two phases switching simultaneously.

Elimination of the shunt also increased the system efficiency and allowed a common source configuration. Since all MOSFET drives reference to the sources of the MOSFETs, a common source configuration allows a common ground for all three phases. This eliminates the need for a floating drive or floating control circuits. It simplifies the design, since differential measurements and drives are no longer needed. Common mode rejection of the floating circuits was also a problem before the common source configuration was used.

A 30 kWe arcjet PCU was built on the basis of the above design consideration. This PCU was shipped to Rocket Research Company (RRC) for a system proof-test with their 30 kWe arcjet engine. The test was run for over 20 hours with no indication of PCU degradation. (See the Achievements section).

Since the development of the starter circuit was not finished before the RRC test, the arc was initiated by an external power supply. Subsequently, a starter scheme was developed, built, and tested (after the PCU was shipped back to SPI). The circuit was able to start an arcjet simulator with a starting voltage of over 1000V.

ACHIEVEMENT OF OBJECTIVES

An arcjet PCU was designed, built and tested with a full power arcjet- engine. This PCU is capable of delivering 30 kWe to an arcjet engine while actively maintaining the arcjet current at a level controlled by the operator. With a resistance load, as was used in laboratory tests, the output current of the PCU can be set between (essentially) zero and 300 A, as long as the output voltage is maintained between 30% to 70% of the input voltage. (Since the arcjet voltage range is somewhat limited, no effort has been spent on broadening the output voltage range restriction). With an arcjet engine load, the output current range is up to 300 A maximum, limited only by the engine. The output current of the PCU is independent of the output voltage, providing the voltage output does not exceed the design limits.

The efficiency of the PCU is about 95% and is expected to be 96% by using a newer version of the switching MOSFET hybrid.

After the PCU had been subjected to over 20 hours of full power (25 kWe or above) laboratory testing on a resistive load, it was tested with a 30 kWe arcjet engine at RRC. The integrated PCU arcjet system was operated for about an hour in an initial checkout test. During the last 5 minutes of the checkout test, the PCU actually operated at 35 kWe, because the shunt resistor was placed in the anode end instead of the cathode end. As a consequence, about 15% of the cathode current went to the test chamber instead of the anode of the arcjet engine. The test was then terminated (for reasons other than the PCU). The PCU showed no sign of degradation from the overpower testing.

Subsequently, the PCU was tested for 20 hours at or near design power in conjunction with a cathode degradation experiment. Again, the PCU performed flawlessly and with no apparent degradation.

A most interesting result from this 20 hour test is that the arcjet cathode showed no dendrite growth (whiskers) on the tip of the cathode, an adverse phenomenon normally associated with the common laboratory power supply. Since the dendrites are thought to have been the cause for the termination of the long life arcjet engine test at JPL, the PCU may be able to lengthen the life time of the arcjet engine. The present speculation for this significant result is that the small amplitude and high frequency of current ripple and the real-time surge current limit associated with the PCU power supply greatly decreases cathode erosion.

The PCU is also now equipped with an integrated starter circuit, taking advantage of the energy storing capability of the output inductors, using them to create an inductive voltage spike in excessive of 1000 V to initialize the arc. The starter circuit was tested successfully with an arcjet simulator developed at SPI, although it has not been demonstrated with an actual arcjet due to funding constraints.

The success of this arcjet PCU is an important milestone in electric propulsion development. The feasibility of a high efficiency (no ballast resistor) and high power (30 kWe or higher) arcjet PCU, using essentially off-the-shelf commercial components, has been established. The full power test also suggests a possible means to increase the arcjet engine useful lifetime. A flight-qualified, compact, low mass PCU appears to be a very realistic and achievable goal.

TECHNICAL DISCUSSION

MAGNETIC CURRENT SENSING

Advantage of Current Transformers

Current transformers are used widely for current measurement because of good noise immunity and low power dissipation. The power dissipation of a current transformer is equal to the square of the current multiplied by the insertion impedance. The insertion impedance equals the resistance of the termination resistor divided by the square of the number of turns of the current transformer.

$$P = I^2 \times R_i$$

$$R_i = R_t / N^2$$

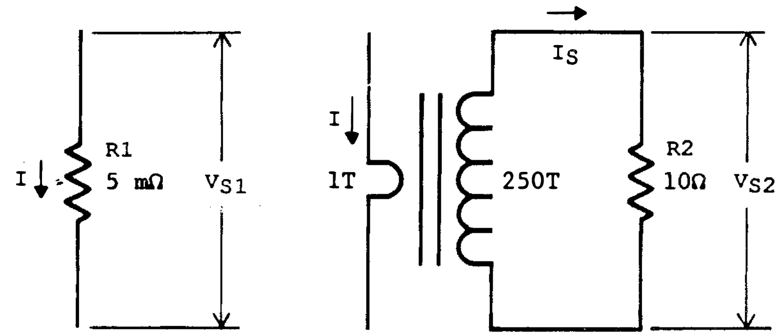
Where
- P = Power dissipation
- I = Current being measured
- R_i = Insertion impedance
- R_t = Resistance of termination resistor
- N = Number of turns

The following example illustrates the benefit of using a current transformer. (Fig. 5)

Current to be measured: 100 A (I)

Case 1 (Shunt) Fig 5A	Case 2 (250 Turn Current Transformer) Fig 5B
R_1 = 5 mΩ (shunt resistance)	I_s = .4 A (current in the secondary winding = I/N)
V_{s1} = 0.5 V ($I \times R_1$)	R_2 = 10 Ω (termination resistance)
P_1 = 50 Watt ($I^2 \times R_1$)	V_{s2} = 4 V ($I_s \times R_2$)
	P_2 = 1.6 Watt ($I_s^2 \times R_2$)

In case 1, the shunt resistor is used directly to measure the current. In case 2, a 250 turn current transformer is used with a 10 Ω termination resistor. The power dissipation is 50 watts in the case of the shunt and only 1.6 watts in the case of the current transformer. Furthermore, the measured voltage with the current transformer is eight times higher than the one with shunt (4 V vs 0.5 V). Because the noise level should be about the same for both cases, the signal-to-noise ratio is therefore



(a) Shunt Resistor (b) Current Transformer

Figure 5. Current Transformer Example

improved by 800% and the power dissipation is reduced by 97% for a current transformer instead shunt.

There is little doubt about the benefit of a current transformer. However, a regular current transformer can only be used to measure a.c. current. In the arcjet PCU design, current measurement is needed for both the current servo loop and the current-mode PWM in the inductor circuit. These have both a.c. and d.c. components. If a regular current transformer were to be used, only the a.c. component of the inductor current could be sensed at the output (secondary winding) of the current transformer and consequently a simple regular current transformer cannot be used. An innovative approach for using the current transformer is implemented in the arcjet PCU. This approach maintains all the benefits of a regular current transformer (high signal to noise ratio and low power loss) and still creates a useful measurement for the control circuit.

The output current we needed to measure was the sum of I_d (the current flows through the switches). Both I_d and I_s could be measured by a current transformer. An operational amplifier was then used to synthesize the output current measurement by a summing circuit. This technique of measuring I_d and I_s and to synthesize the output current had been successfully applied in the arcjet PCU and eliminated the need of the shunt resistors.

FEEDBACK CONTROL OF THE PCU

The feedback control circuit is responsible for turning the switches on and off in the buck regulator in such a way as to maintain the desired arcjet current or power. We have investigated three different types of control circuits. This investigation combined analytical methods, a computer simulation, and our experimental experience with the laboratory power conditioning unit. Our results show that the modified current mode feedback circuit provides the best combination of stability, control and redundancy.

Duty Cycle Feedback

In the duty cycle feedback circuit, the current to the arcjet is continuously monitored. A time average of this current is used to set the duty cycle for the buck regulator switches. The higher the time average current the lower the duty cycle. This feedback system is simulated on a computer for the circuit parameters shown in Figure 6. Figures 7 and 8 show sample results from this simulation.

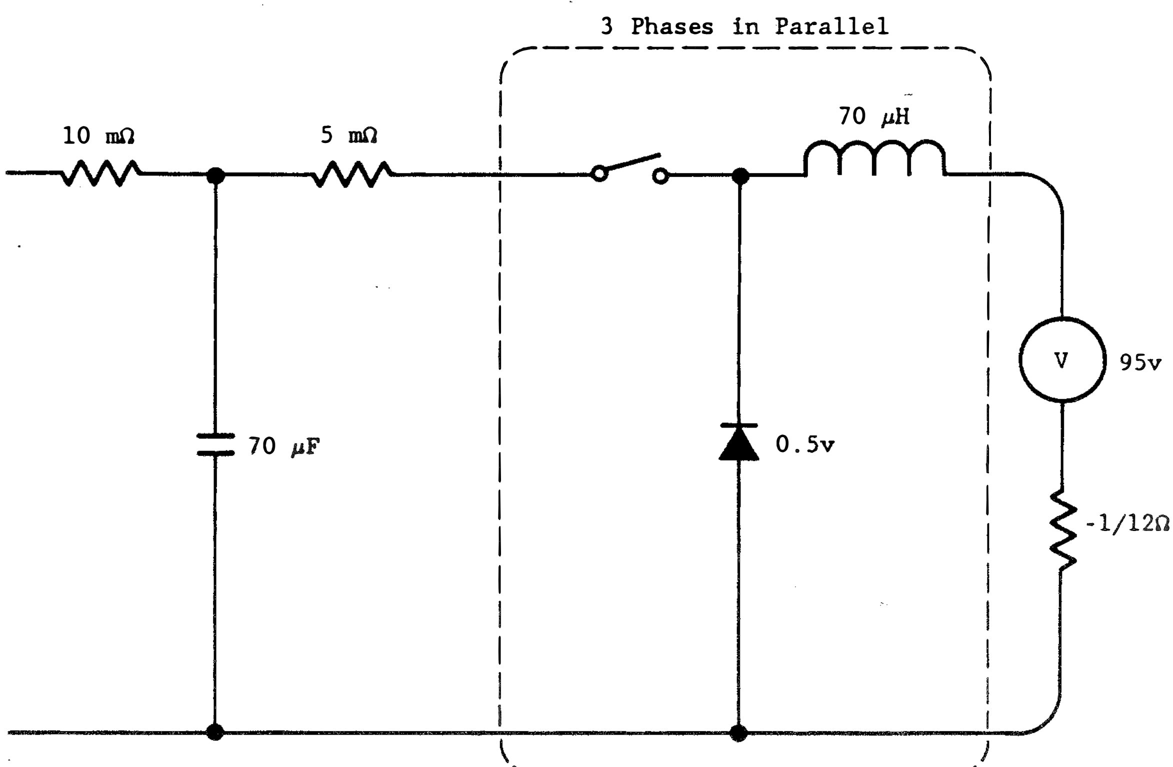


Figure 6. Simplified Circuit Used for Simulation

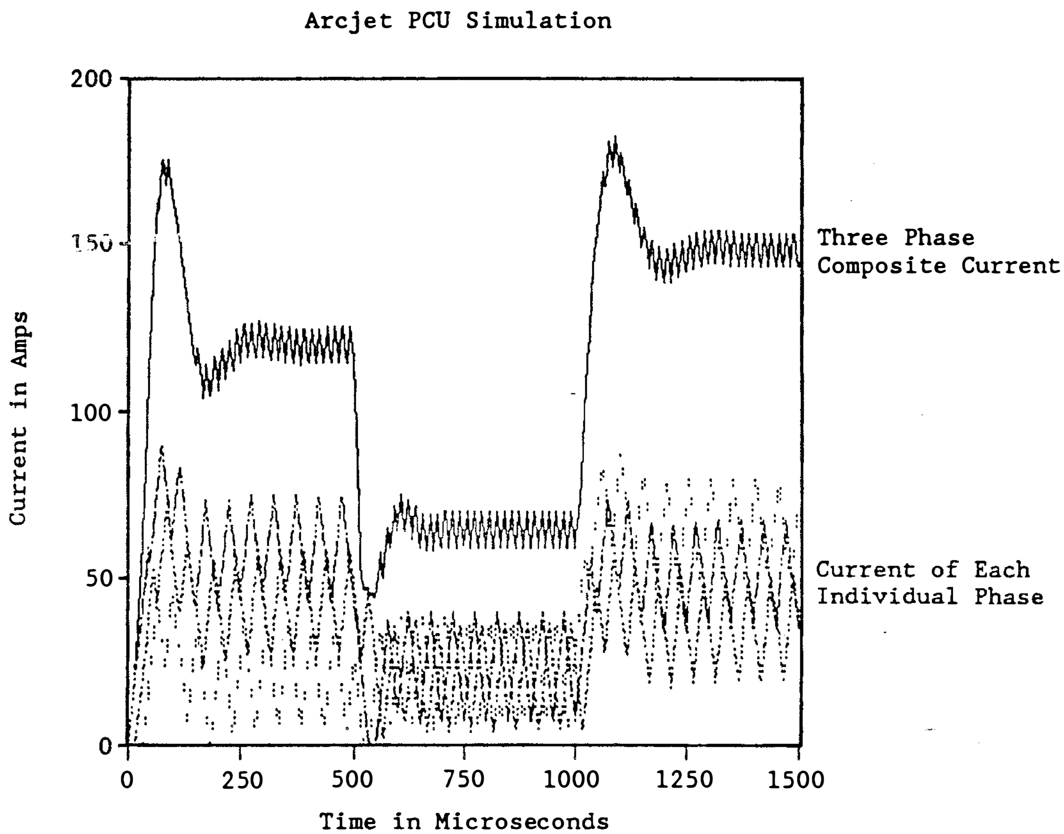


Figure 7. **Duty-cycle Feedback**

Two key features of this feedback system were found. One is that there is a slight over-shoot and ringing when the desired current is adjusted. This ringing indicates a natural frequency for the feedback system which might cause severe oscillations if the arcjet also oscillated near that frequency. The second feature is that each phase of the 3 phase buck regulator tended to assume a different current level. This feedback system had no mechanism for driving each phase to a similar share of the load.

Current Mode Feedback

The second feedback system regulates not the duty cycle but the maximum current in each phase. In this system a clock turns on each phase periodically, and the phase is turned off when its current exceeds some preset maximum. See Figure 9. Since this circuit controls the current in each phase individually, this circuit does not have one of the problems shown by the duty cycle feedback system. Extensive analysis and experimentation has shown that this circuit can, however, produce sub periodic waveforms as shown in Figures 10, 11 and 12. These waveforms are undesirable.

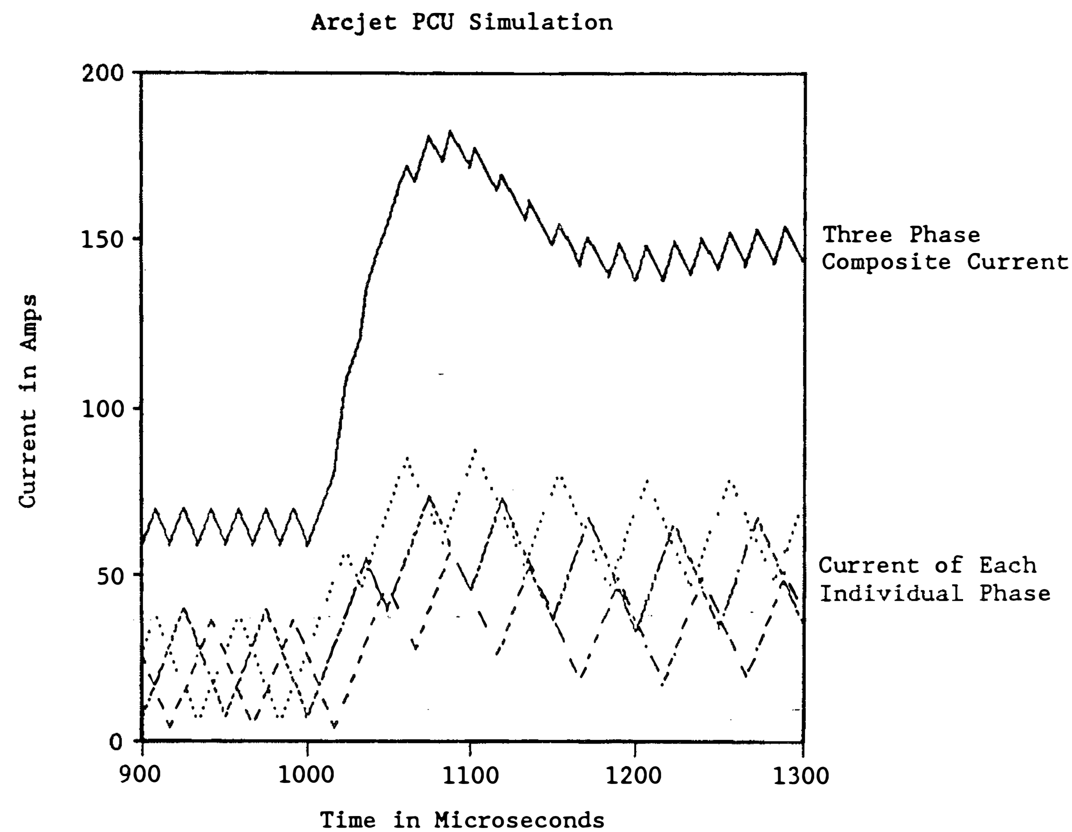


Figure 8. Duty-cycle Feedback

Modified Current Mode Feedback Circuit

Our analyses of, and experience with, the previous two feedback systems led us to a third system which combines elements from both. This system appears to provide good stability and control. The control circuit also has a higher degree of redundancy than the duty cycle feedback system.

In this circuit a clock periodically turns on each phase. Each phase then stays on until its current exceeds a limit. This is similar to the regular current mode feedback system, described previously, except that the current limit is time varying. The current limit for each phase declines linearly during the time that the phase is on. See Figure 13.

Simulations of this circuit were performed and are shown in Figures 14, 15 and 16. The current waveforms are seen to be quite regular and periodic. All phases are operating near the same current level. There is no evidence of any ringing.

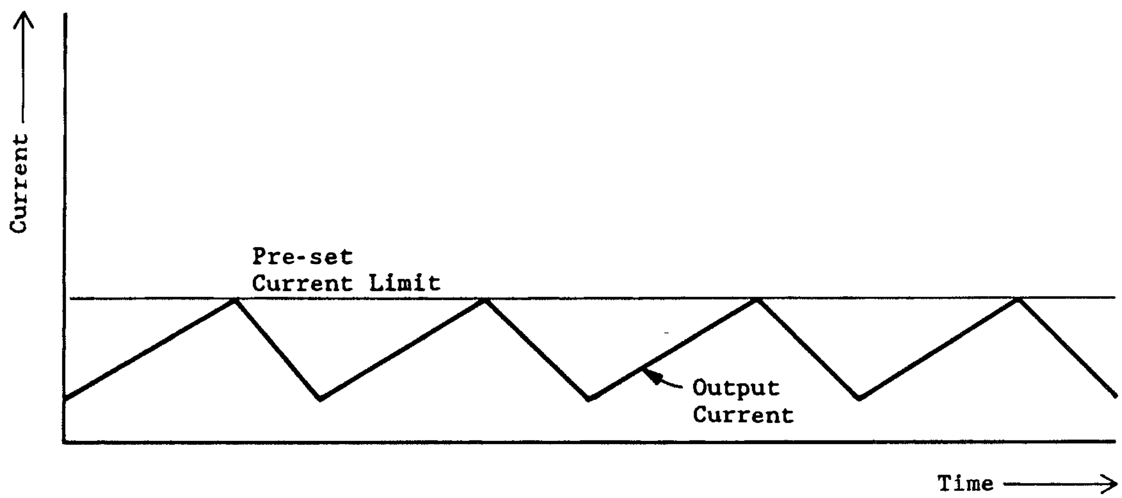


Figure 9. <u>Current Mode Feedback with One Phase.</u>

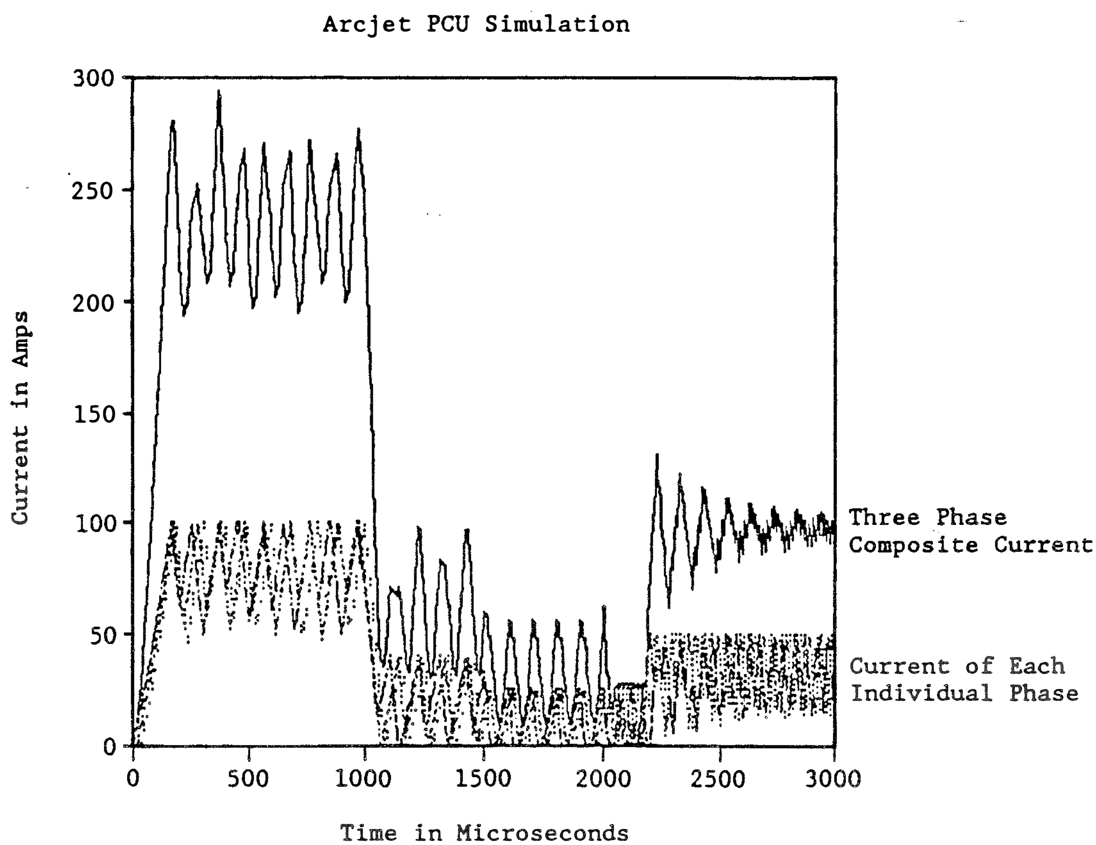


Figure 10. <u>Current-Mode Behavior vs Time.</u>

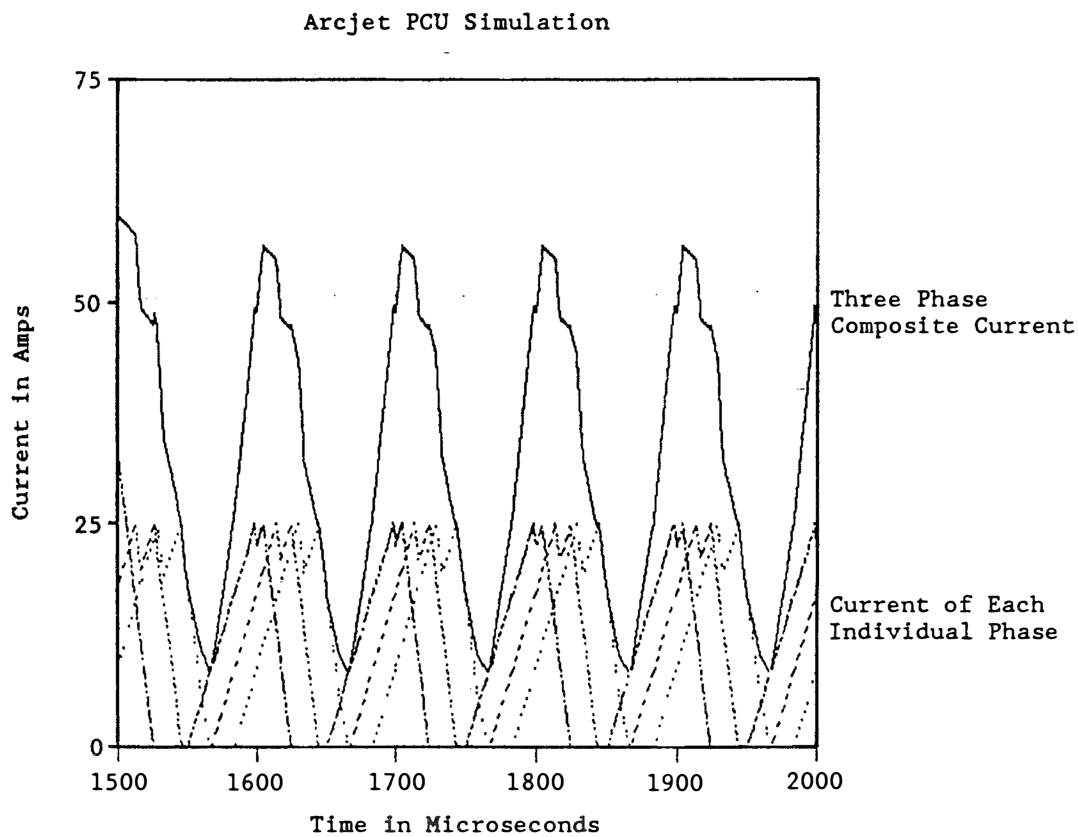


Figure 11. Current-Mode Feedback

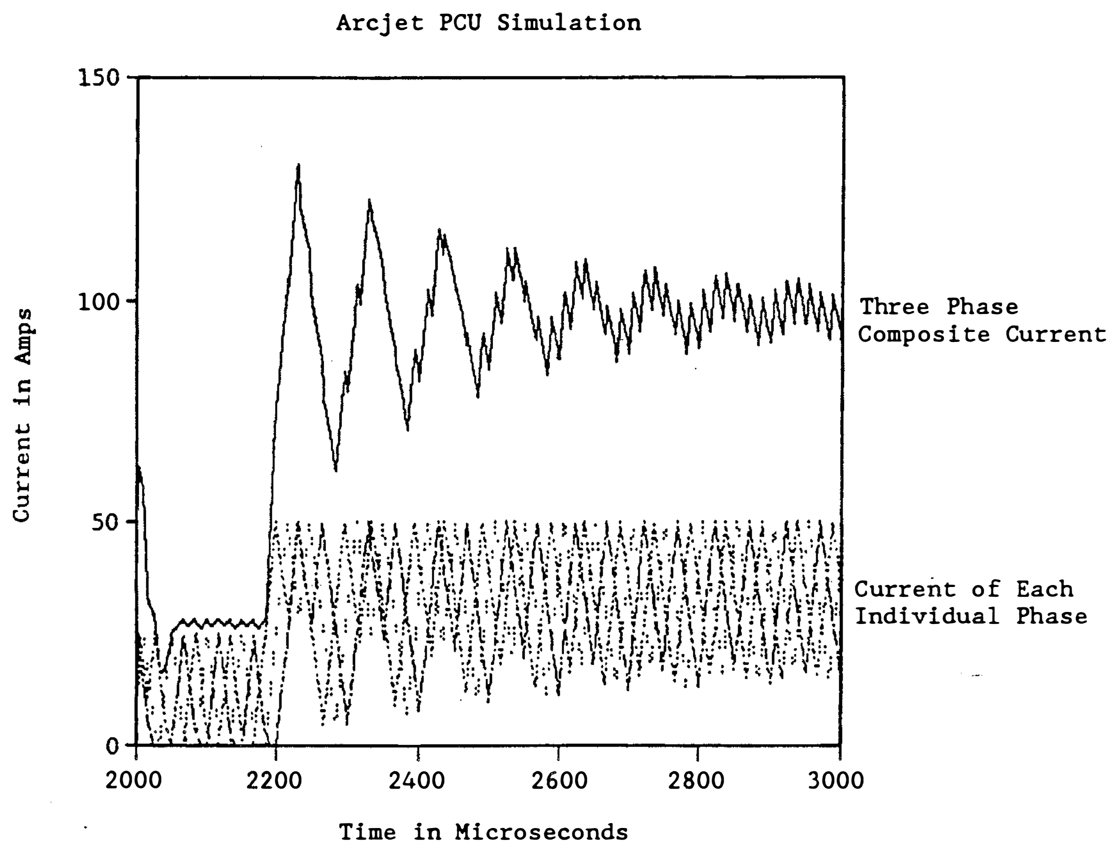


Figure 12. Current-Mode Damped Oscillation

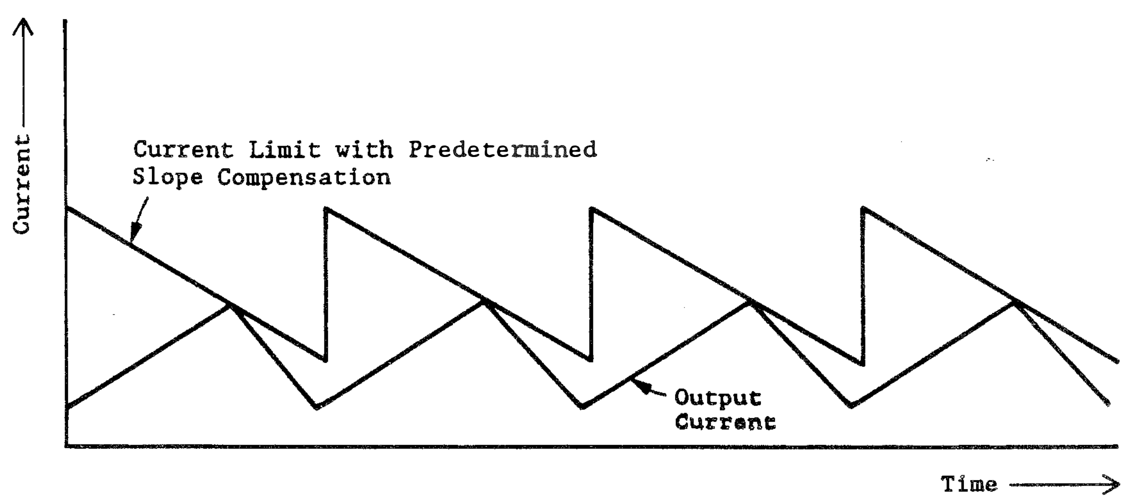


Figure 13. Modified Current Mode Feedback with One Phase

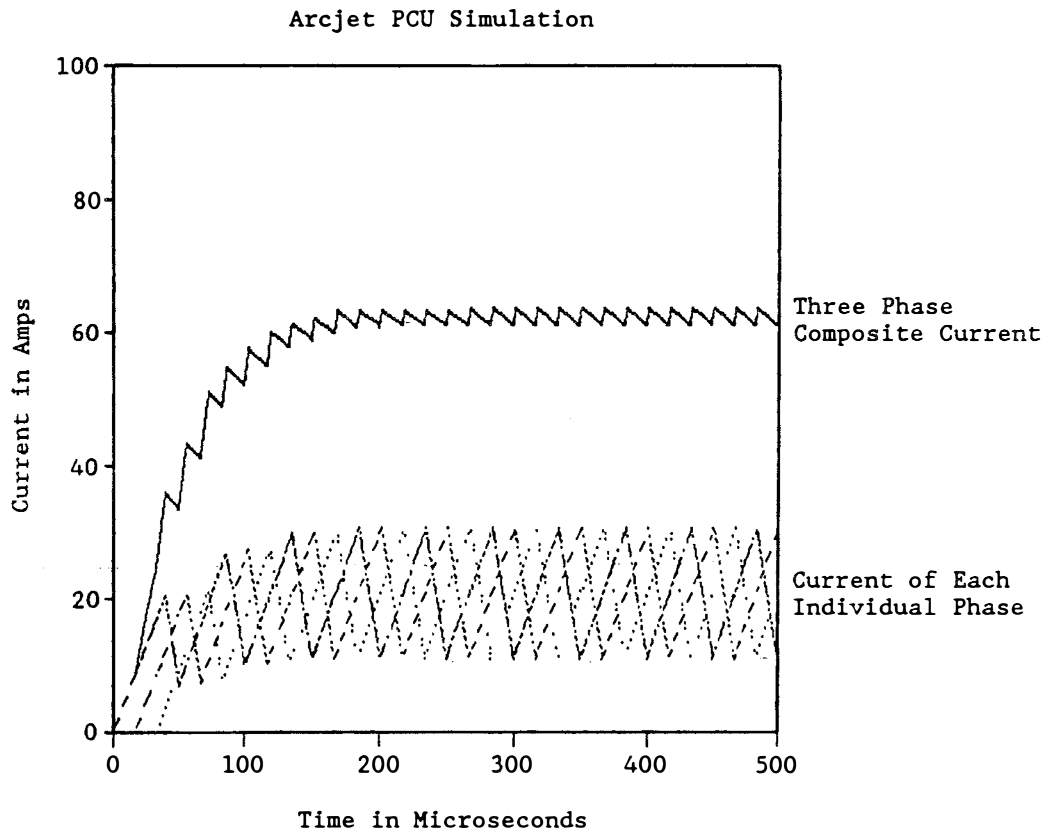


Figure 14. Modified Current Mode Feedback Starting From No Current At t=0

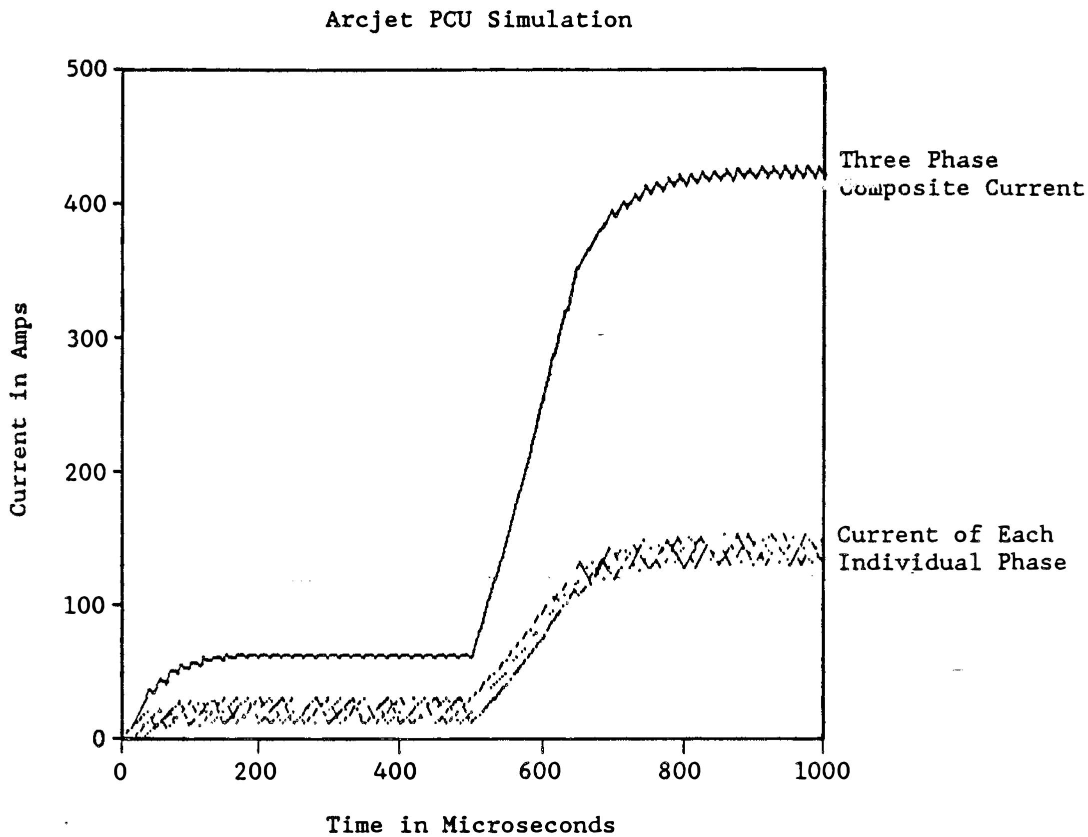


Figure 15. Modified Current Mode Feedback

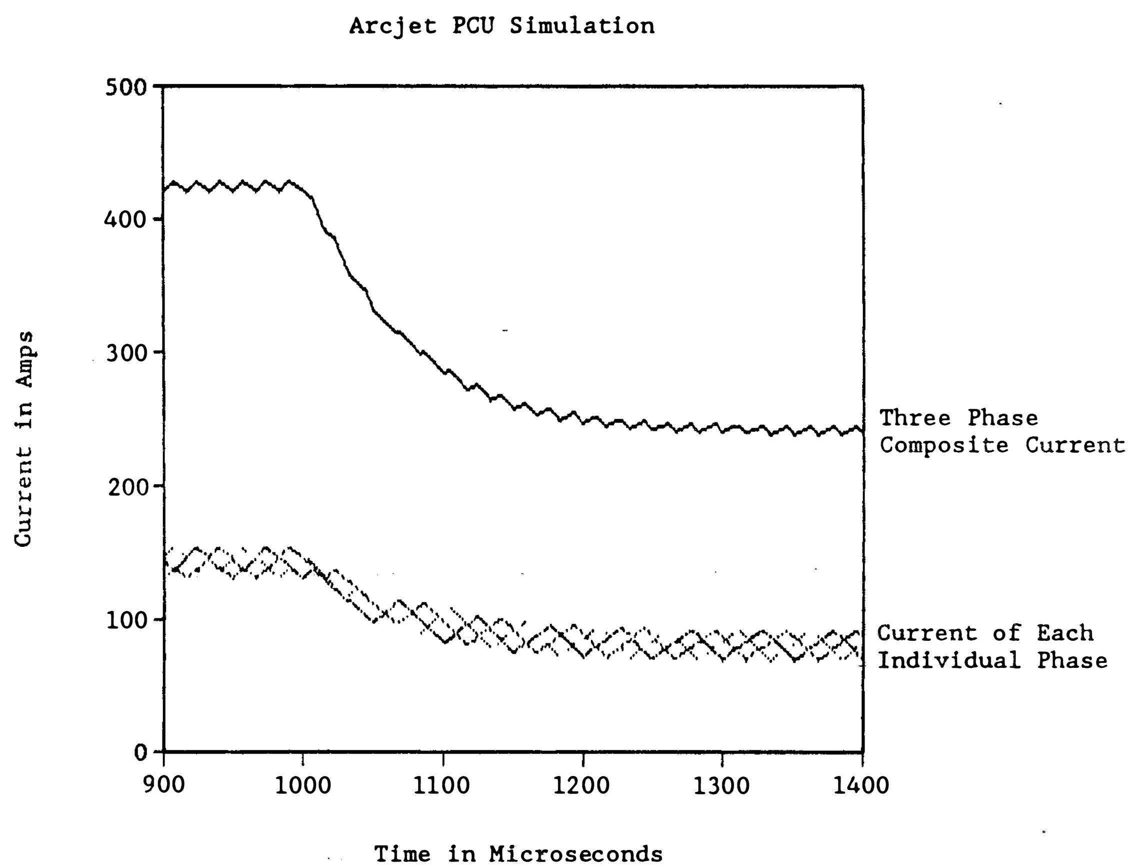


Figure 16. Modified Current Mode Feedback

STARTER

The arcjet thruster requires a high voltage across the cathode and the anode to initiate the arc. For the 30 kWe thruster, the breakdown voltage is about 1000 V. Many different approaches can be used to generate this voltage. The following are the possibilities that have been considered.

1) **Independent Floating power supply and a blocking diode.** The RRC test used this approach. This required more circuitry and weight, because it did not take advantage of the existing circuit components.

2) **Separate low voltage winding on Output Inductor.** As the NASA Lewis 1 kWe Arcjet PCU (Note 1). This one of 2 approaches that take advantage of the output inductor. Therefore, it is a more effective design than the independent supply. However, it is not suitable for this arcjet PCU for two reasons. First, this is a three phase PCU so that there are three separator output inductors. It will require 3 separate low voltage windings to perform the function. Second, the low voltage winding is required to switch a very large amount of current. A voltage step down transformer is also a current step up transformer. The current in the low voltage winding is equal to the inductor current times the voltage step down ratio (turns ratio). For low power and low current design, this current step up may not be a serious problem. For the high power design, the inductor current is on the order of 100A. Even though it is not necessary to use the maximum allowable current to start the arc, the current required to start the arc is still very high. The inductance of the output inductor is roughly inversely proportional to the output current, providing the switching frequency is the same. Therefore, a high current system is always designed with lower output inductance. Since the inductive flyback voltage equals L *dI/dt, and the output inductance is lower with higher power system, the dI/dt needs to be higher. The switching time is not going to be shorter, therefore, very high current is required. In this PCU, about 50 A per phase is needed. If low voltage windings were used, the switch with the low voltage winding current will be required to interrupt a very high current, ~100 amps. Therefore, this approach has not been selected for this PCU.

3) **Direct Short-Circuit Output Switch.** This is the most direct approach. A switch with very low resistance is connected in series between the anode and the cathode of the arcjet thruster. For starting the arcjet engine, the switch is momentarily closed and the current in the inductor builds up. Then, the switch is opened to interrupt the inductor current. This generates an inductive voltage transient across the arcjet engine known as the flyback action. This approach requires a minimum of components. It only requires a timer, a series current limit resistor and a power switch. Therefore, it is the approach that was selected in this PCU.

After the arcjet is started, the arcjet current is controlled by the PCU. However, the transition between the zero current and the stable current is not trivial. This period may be the most erosive period for the cathode because of the high transient current. When the 30 kWe arcjet thruster was tested with a laboratory supply with a ballast resistor in RRC, the initial surge current observed was as high as one thousand amperes. The maximum steady-state current was only around 300 A. When this arcjet PCU was tested at RRC, the surge current was also about 450 A. This excessive surge current problem was later solved in a separate SBIR contract, named Improved Flight-type Arcjet Power Conditioner.

EXPERIMENT AND TEST DATA

This section describes six milestones experiments conducted as part of the arcjet PCU development.

Test descriptions, results and brief discussions are presented. The four milestones are:

1) The completion of a subscale breadboard and testing with an arcjet.
2) The completion and full power laboratory resistive load test of the PCU.
3) The full power operation of the PCU with 30 kWe arcjet thruster.
4) The comparison test of arcjet cathode erosion with and without the PCU.

TEST ONE: SINGLE PHASE SUBSCALE BREADBOARD TEST

The single phase breadboard was first tested with a resistive load at 10kWe. Since the primary interest was in the performance of individual components, no efficiency measurement was made. This breadboard was then shipped to Rocket Research Company (RRC) and test with a 30 kWe ARCJET thruster operating at 10kWe power lever.

The power source was a Rapid Electric Company three phase SCR controlled d.c. supply. The input voltage to the PCU was set at 150 V. There was a 0.1 Farads capacitor bank connected between the d.c. supply and PCU. The cooling loop of the PCU was not activated due to a grounding problem.

At the time of this test, the starter current has not been fully developed. Rocket Research Company provided a high voltage source about 800 V to initiate the start up of the arcjet. Breakdown (ionization of the propellant) occurred at 700 volts. Upon ionization of the gas, the arcjet experienced a current overshoot of about 50%. The PCU then began to regulate the current within a two millisecond time period.

The ammonia flow was initially set at 1.2×10^{-4} m/s and, after start up, adjusted to 2.0×10^{-4}. Cathode current was constant at 70A. Voltage across the arcjet was about 60 V. As the run continued, the voltage across the arcjet began to fall to about 40 V. Current began to rise one minute after the start.

At one and a half minutes the MOSFET were shorted and the test was terminated. Investigation of the failure indicated that over-heating was the major cause due to the insufficient cooling. Although the test was short, the test proved that the PCU was capable of stable operation with an arcjet which was characterized by a negative dynamic impedance.

TEST TWO: THREE PHASE TEST WITH SOLID STATE LOAD/EFFICIENCY MEASUREMENT

The solid state load test was performed in 5 hour intervals for a total of 20 hours. At the end of each five hour run, the system was turned off and checked for excessive heating of components. At the end of the first run, the free-wheeling diodes were found to be very hot. Further investigation revealed the free-wheeling diodes had not been mounted or torqued down tight enough. The problem was corrected and the testing continued. The voltage and current waveforms of the steady state operation are shown in Figure 17. Figure 17 is an oscilloscope photograph of the output current ripple (top trace) and the voltage waveform across the switch (bottom trace). This photograph was taken after five hours of continuous operation on a solid state load. To obtain the top trace a Pearson current probe part #4428 was used. The bottom trace was obtained with a oscilloscope probe referenced to the source of one phase and the probe itself was contacting the drain of the same switch (MOSFET).

At the end of the third five hour period, efficiency measurements of the system were made. Results of the efficiency measurements showed an efficiency of 97.2%. The equipment used to take the data included: two 300 amp shunt resistors with 1% accuracy, one shunt resistor placed in the output node current path of the PCU. The other shunt resistor placed on the input current path of the PCU. The voltage meter used to take the efficiency measurement was a Beckman Industrial Model 360. The voltage meter was set in the DC voltage mode. The output power was approximately 26.8 kWe. The efficiency measurement was as high as 97% efficiency at the high power level. The result is shown in Table 1.

We suspected the high measured efficiency. Further investigation decided that the Beckman Model 360 was capable of making accurate measurement with high frequency noise. In addition, two shunt resistors used in efficiency measurement were put in series to check with each other. The result indicated a 2% difference between the two shunt resistors. We decided that a more accurate measurement setup was needed. Therefore, a set of new current shunt resistors with an accuracy of 1/4% and a Hewlett Packard DC Multi-meter (Model #3456A) were purchased. After implementing the new shunt resistors and HP digital multi-meter, a series of efficiency measurement at different power levels was performed. The highest power level during the test was 28.2 kWe. At that power, efficiency was 94.4%. The impedance of the resistive load was 0.332 Ω. After repeating the efficiency measurement three times and obtaining very consistent data, it was believed the results was valid to within 1%. Set up for the efficiency measurement is shown in Figure 18. The result of the efficiency measurement is shown in Table 2.

Figure 18 shows how the efficiency measurements were taken. The efficiency measurement was performed at SPI on a solid state load of .33 ohms. Input power and output power measurements were taken at six different power levels. We also

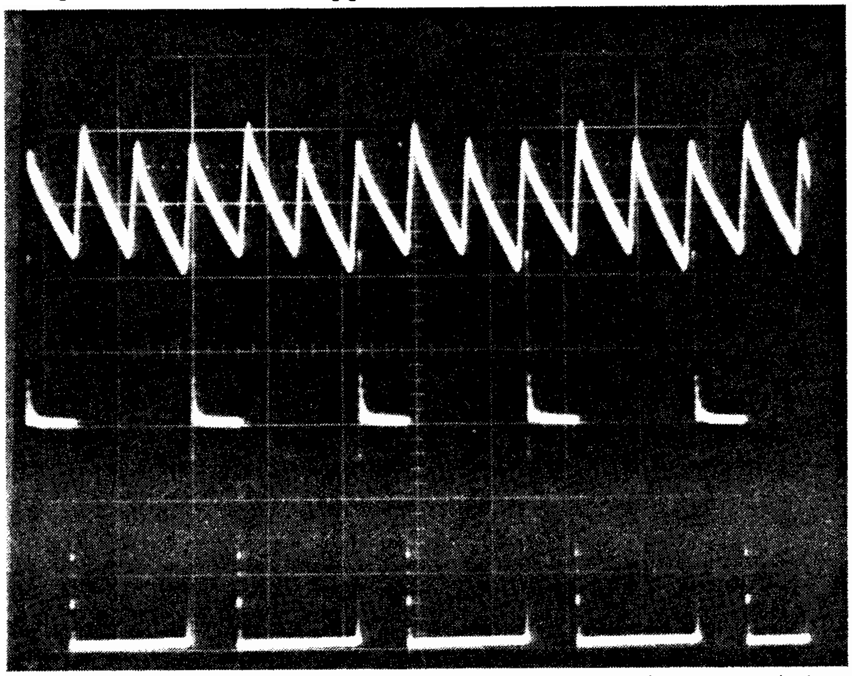


Figure 17. Voltage and Current Waveform of the PCU

Table 1. Power Supply Efficiency Data

V_{in}	I_{in}	P_{in}	Efficiency
V_{out}	I_{out}	P_{out}	
150	47	7,050	94%
49.7	134	6,659	
150	68	10,200	95%
60.1	162	9,736	
150	90	13,500	96%
69.9	187	13,071	
150	118	17,700	96%
80.2	213	17,082	
150	148	22,200	96%
90.1	238	21,443	
150	179	26,850	97%
100.0	262	26,200	

Device Under Test: 30 kWe Arcjet

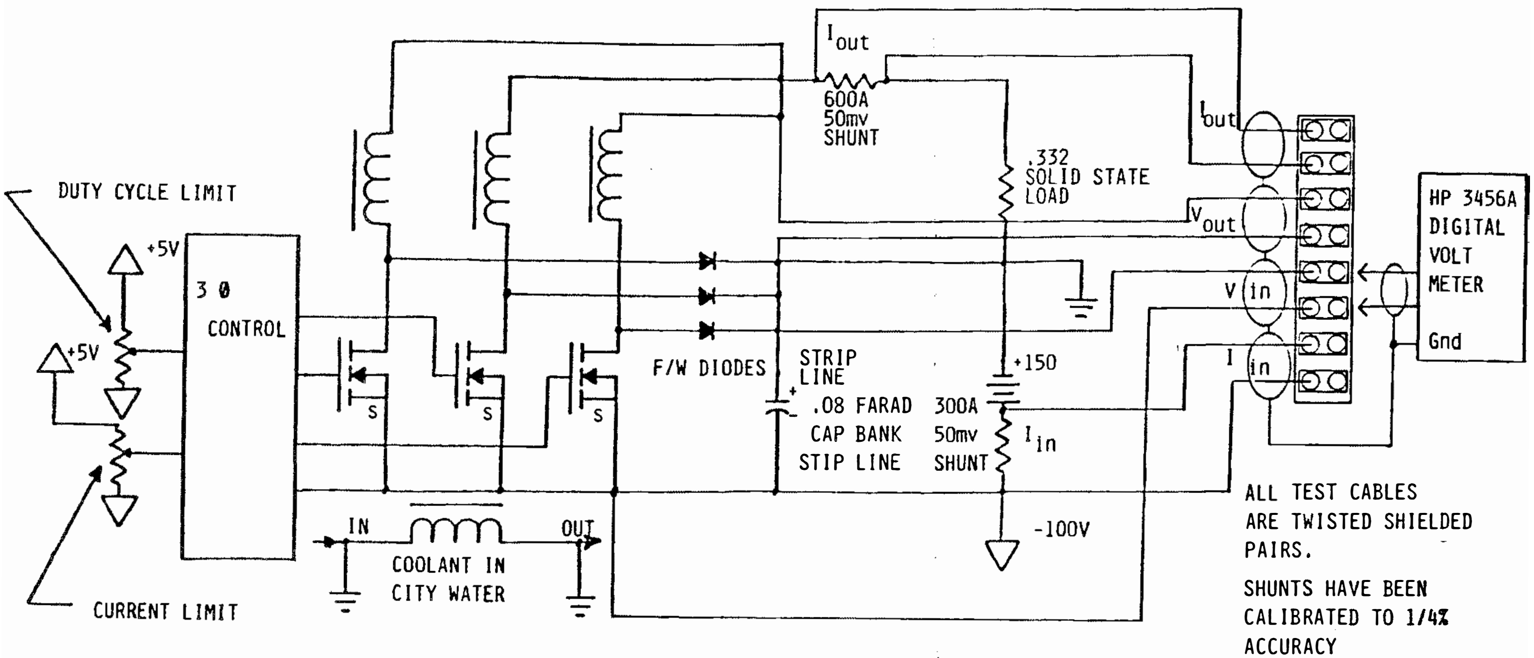


Figure 18. Efficiency Measurement Set-up Diagram

Table 2. Power Supply Efficiency Data

V_{in} / V_{out}	I_{in} / I_{out}	P_{in} / P_{out}	Efficiency
150.69	9.28 mv / 55.68 A	8,378.4	93.2%
50.119	12.985 mv / 155.82 A	7,809.5	
150.69	13.268 mv / 79.60 A	11,994.9	93.8%
60.361	15.556 mv /186.67 A	11,256.3	
150.55	17.91 mv / 107.46 A	16,178.1	94.6%
70.625	18.057 mv / 216.68 A	15,303.3	
150.49	22.894 mv / 137.36 A	20,671.9	94.4%
80.175	20.288 mv / 243.46 A	19,519.1	
150.39	29.09 mv / 174.54 A	26,249.1	94.6%
90.650	22.817 mv / 273.80 A	24,820.3	
150.32	33.08 mv / 198.48 A	29,825.5	94.4%
96.850	24.238 mv / 290.86 A	28,169.4	

Device Under Test: 30 kWe Arcjet PCU Solid State Load
Input Shunt: 300 A - 50 mV
Output Shunt: 600 A - 50 mV

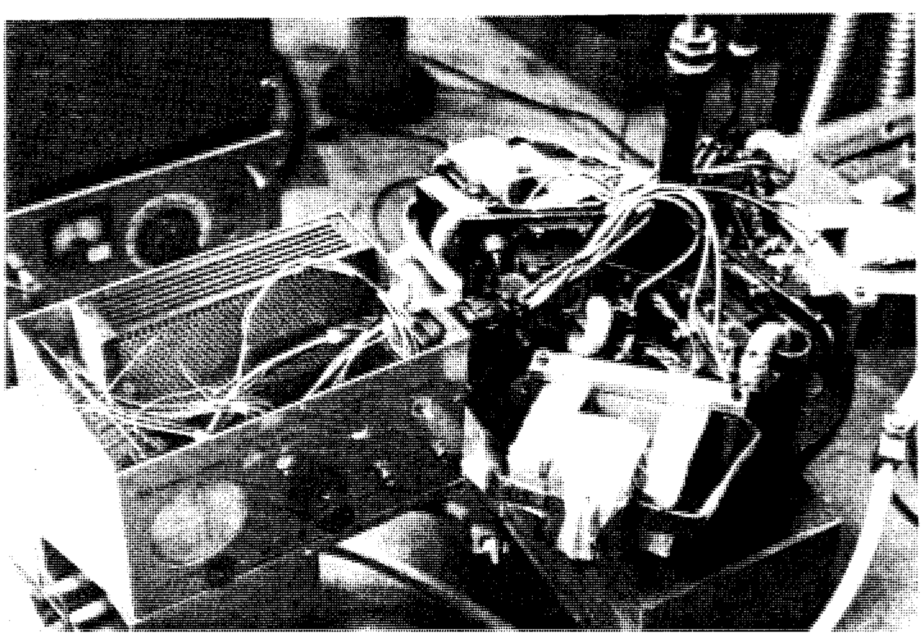


Figure 19. Test Set-up 30 kWe AFAL at Rocket Research

used precision shunts with a 1/4% accuracy and a meter with .01% accuracy. The measurements were obtained by using the average d.c. mode. The EMI noise made the true RMS measurement very unreliable.

TEST THREE: THREE PHASE TEST WITH ARCJET LOAD.

The test of the PCU with the arcjet thruster was performed at RRC in January 1988. The test setup is shown in Figure 19. Figure 19 is a block diagram of the actual test layout at Rocket-Research. The starter switch box seen in this figure was used in conjunction with a high voltage source to provide the start pulse for this test. The starter was a high voltage power supply provided by RRC. A 0.1 Farad capacitor bank was placed between the d.c. power source and the PCU to reduce the ripple from the d.c. power supply output because the PCU was designed to receive clean DC power. The outputs of the power inductors on the PCU were tied together via a AWG 4/0 cable. This approach allowed isolated current monitoring of the individual outputs of each phase. A Tektronics d.c. current probe (max 150 A) was used for current measurement. This signal was recorded by a Nicolet digital storage scope which monitored the start event as well as the steady steady operation.

A rough efficiency measurement was made. Results of those measurements revealed a range of efficiency of 93-97%, ± 3%. The current was measured with 300 amp shunt resistors, one placed at the output and one placed at the input of the PCU. The voltages were read with a small digital multimeter. The input voltage to the PCU was recorded directly off the Rapid Electric Input voltage meter. These efficiency measurements are not nearly as accurate as the one obtained in the last section with a solid state load. It is because the Hewlett Packard D.C. meter and high precision shunt were not available at that time.

After running the arcjet for 1 hour in the steady state mode at about 15 kWe the power was raised to 25 kWe. The PCU showed no sign of degradation and the component temperature was around 45°C. At 1 hour and fifty minutes after the start, the output power was raised to over 30 kWe. At that time, the excessive ground current triggered a shutdown and the test was terminated. Because the anode current was measured instead of cathode current, the PCU was actually operated at about 35 kWe at that moment. The voltage and current waveforms are shown in Figure 20 and Figure 21. Figure 20 is for start-up and Figure 21 is for steady state.

Figure 20 reveals the initial current overshoot characteristics at start. The top trace was output voltage of the arcjet and was measured by a Tektronix 1000X voltage probe was used. The bottom trace was the output of one of the phases and was taken with a Tektronix d.c. current probe. The oscilloscope was a Nicolet digital storage oscilloscope. The information was stored in the digital oscilloscope and then transferred to a Hewlett Packard printer.

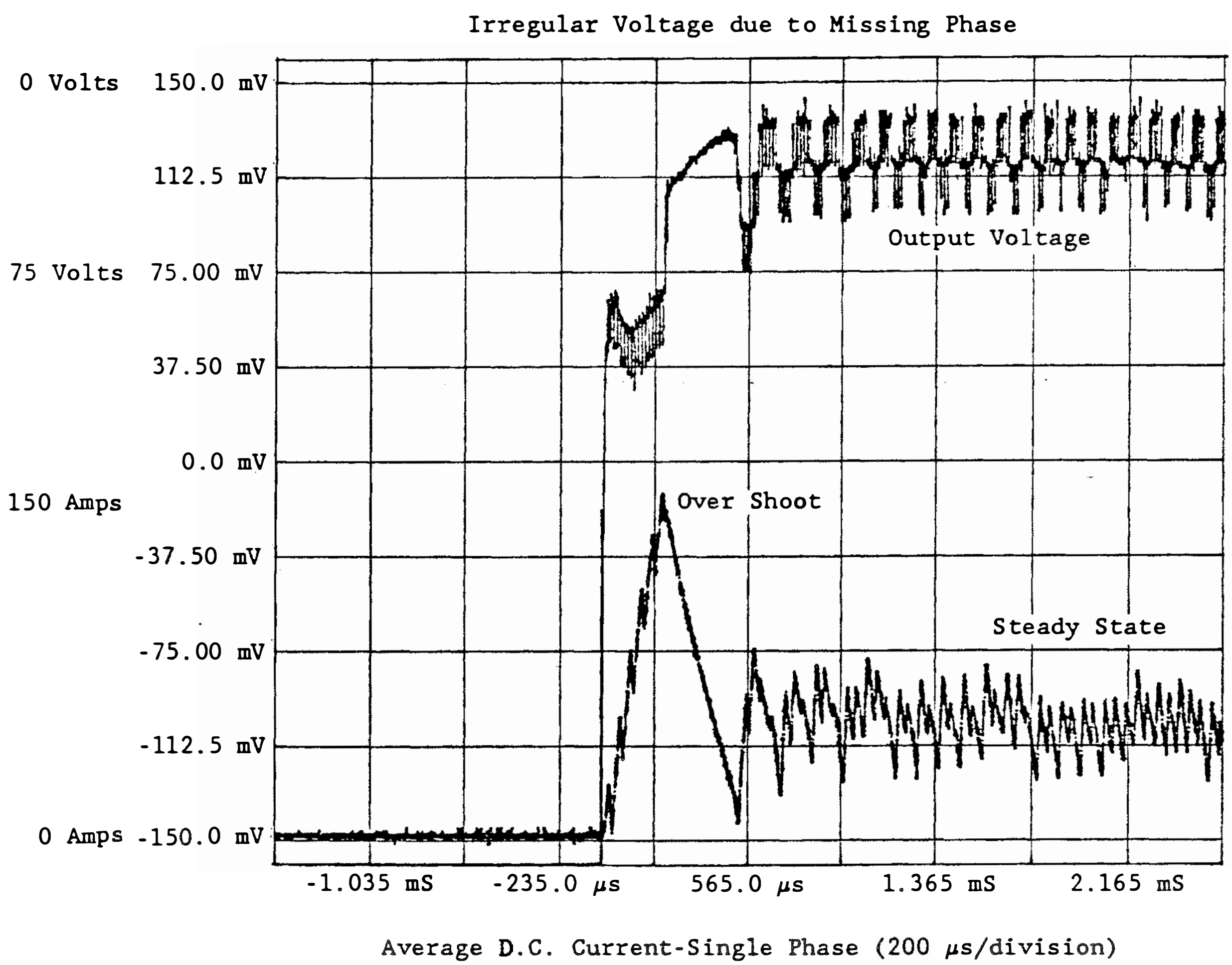


Figure 20. Voltage and Current Waveform at Startup

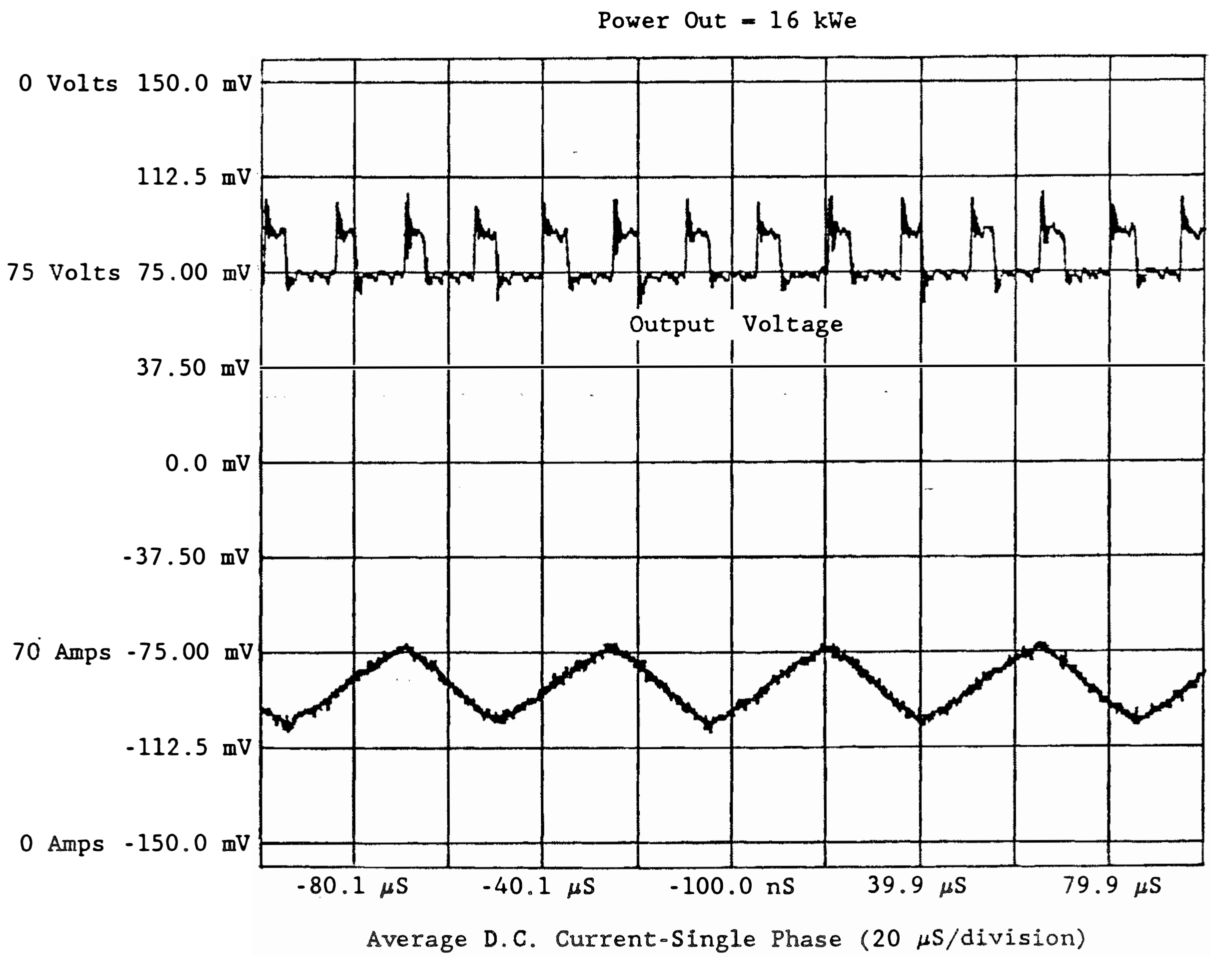
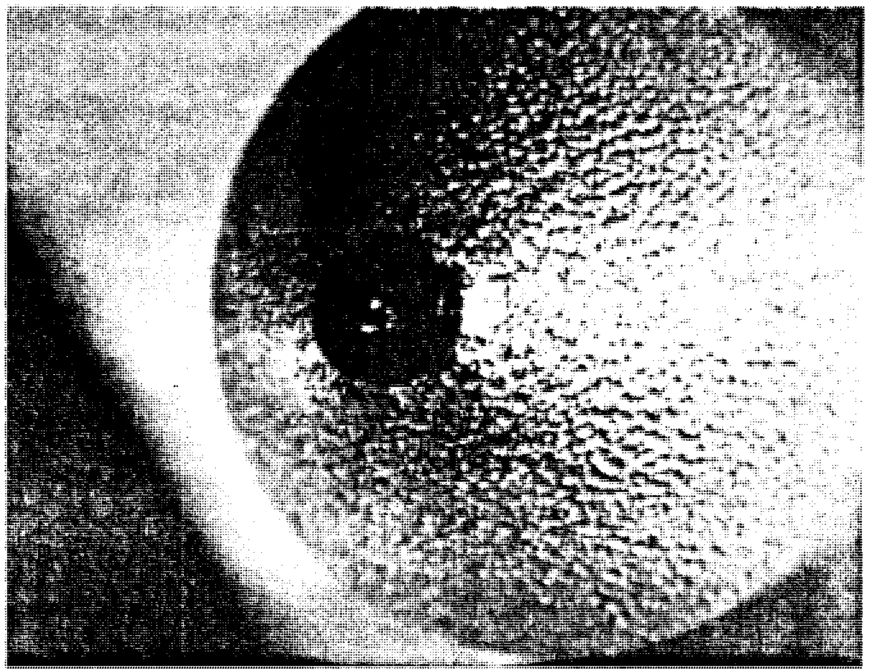


Figure 21. Voltage and Current Waveform of Steady State Operation

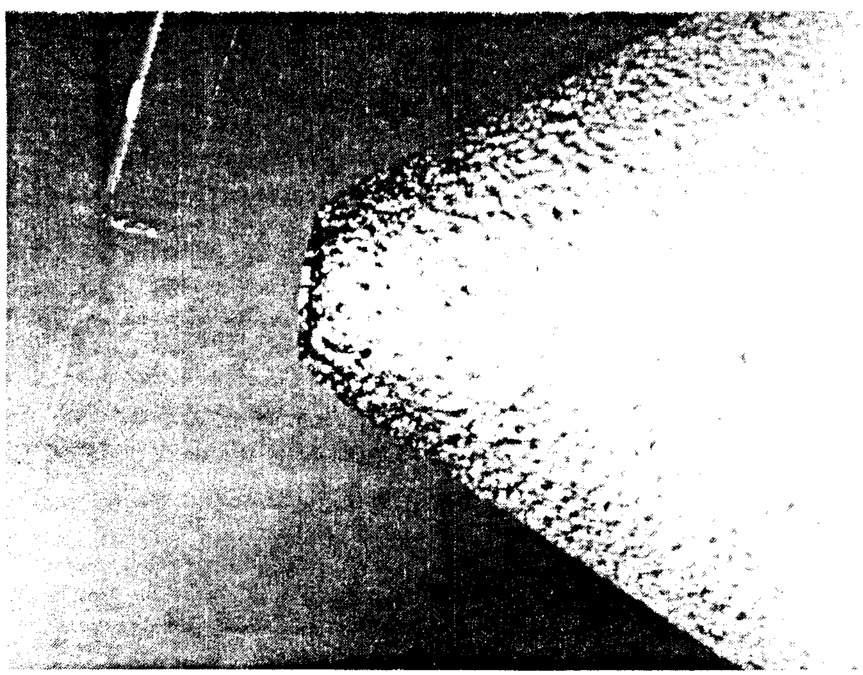
In Figure 21 the top trace shows the output voltage between the anode and the cathode of the arcjet. This oscillogram was taken approximately 10 minutes after the initial start. The bottom trace is the oscillogram of the current in one of the phases.

TEST FOUR: CATHODE DEGRADATION TEST

The PCU was used for the arcjet cathode degradation test in conjunction with a related project. The arcjet PCU reduced the current overshoot to about 400 amps vs. 1000 amps with the ballast resistor approach. The test was for a total of 20 hours at power levels from 15 to 28 kWe. At the end of the 20 hours, the PCU showed no sign of degradation. The set-up for this test was the same as the previous test. The only difference was the current monitored changed from the anode to the cathode. Figure 22 and Figure 23 showed the cathodes after the test. Figure 22 was tested with PCU and Figure 23 was tested with laboratory supply and ballast resistor.

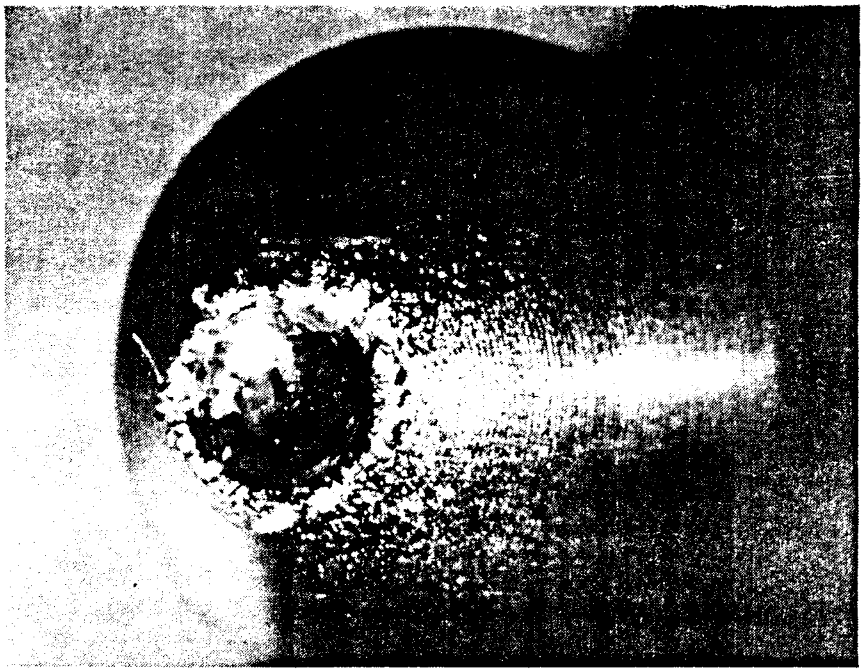


PERSPECTIVE VIEW

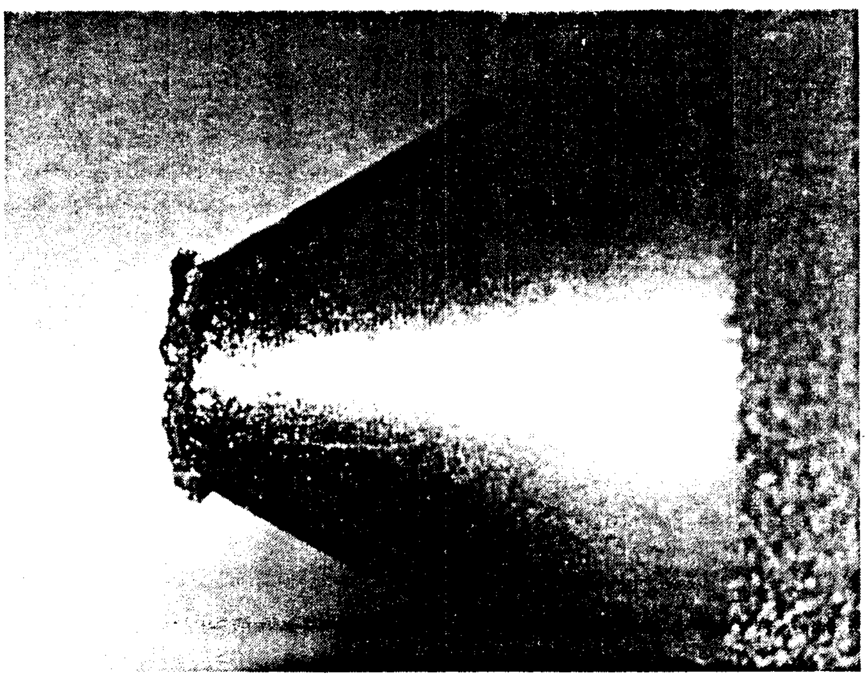


PROFILE VIEW

Figure 22. Post-Test Photos from Test Number 4



PERSPECTIVE VIEW



PROFILE VIEW

Figure 23. Post-Test Photos from Test Number 7